MAY 2017 | VOLUME 19 | ISSUE 2

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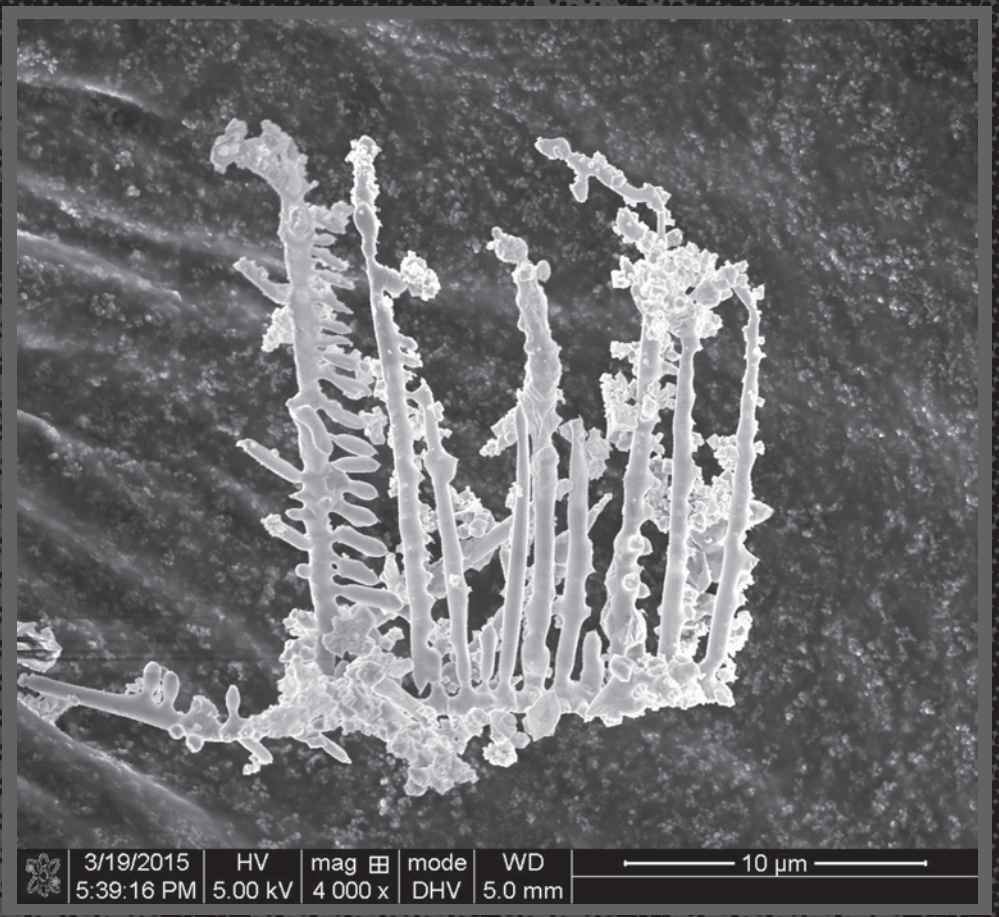
PAGES 38 & 39



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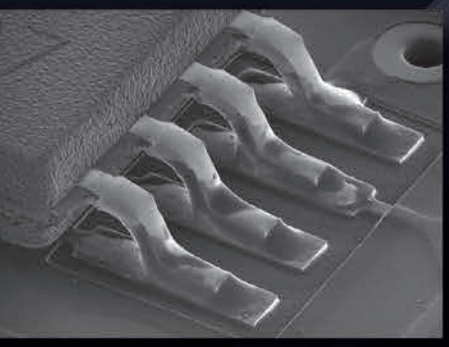
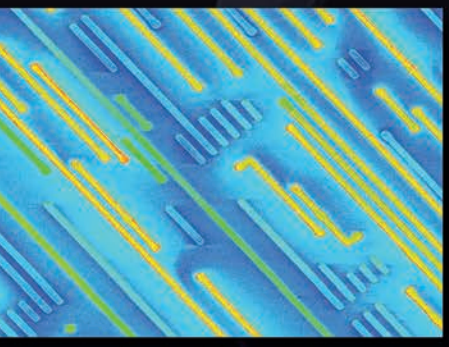
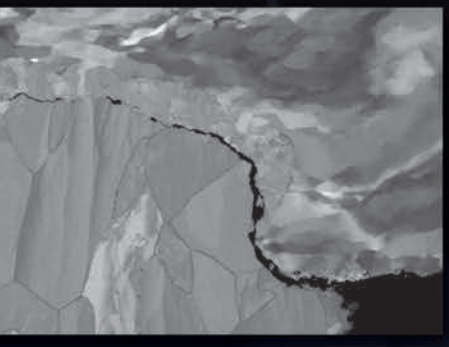


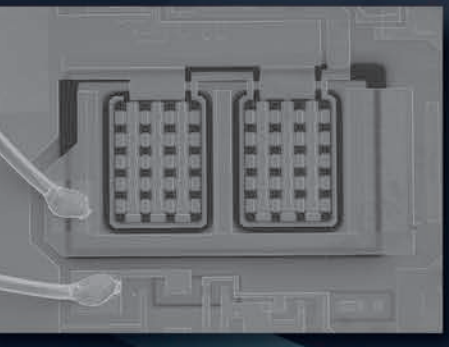
SEM Image of Semiconductor Device



Passive Voltage Contrast (PVC)
image of semiconductor device



Backscatter Electron (BSE)
image of Wire Bond Cross Section



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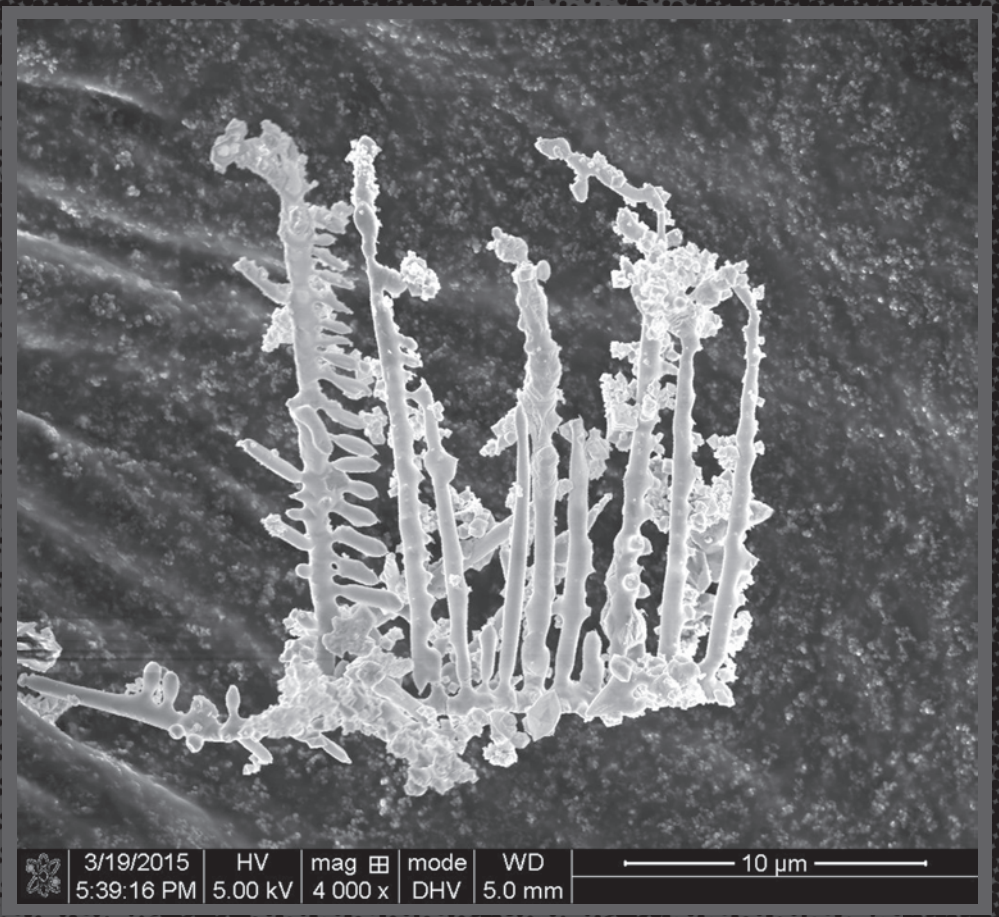

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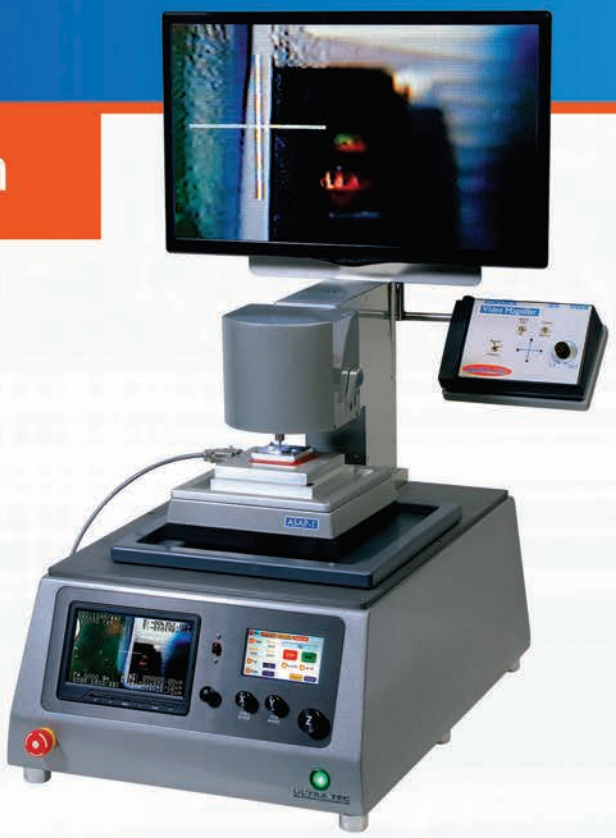

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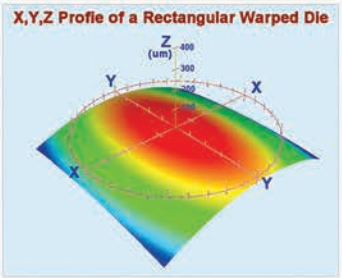

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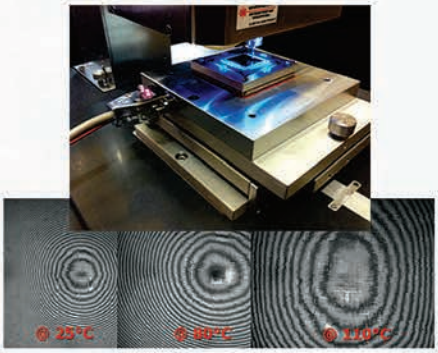

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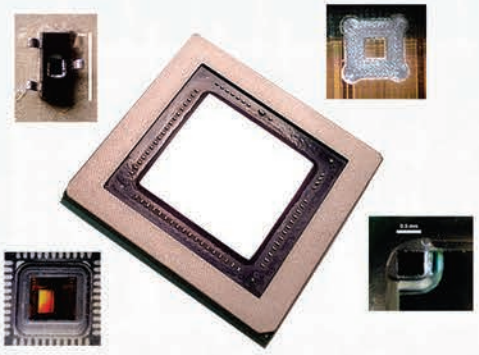

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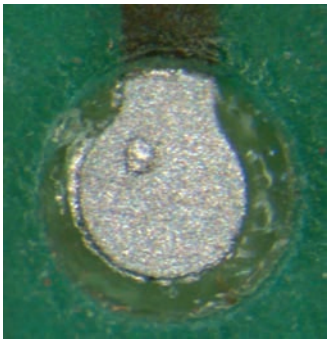

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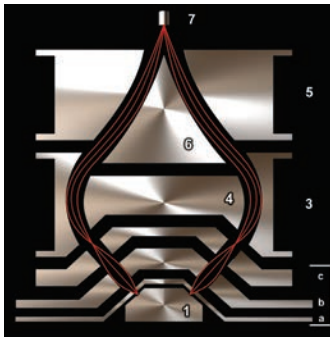

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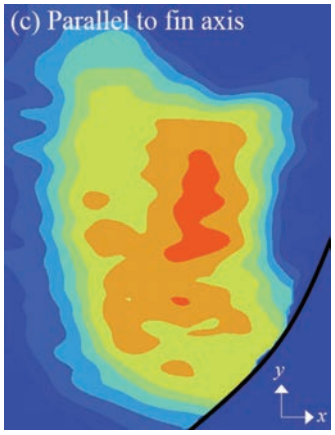

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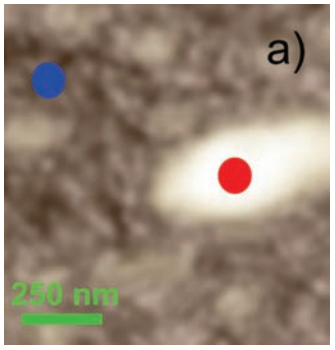

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ABOUT THE COVER

Scanning electron microscopy photo showing lifted-out tin dendrite that caused a flip-chip pin-to-pin short. The dendrite was sitting between ball grid array balls in a flip-chip package where the energy-dispersive spectroscopy (EDS) signal was blocked. The dendrite was lifted out with an Omniprobe and put on carbon tape for EDS analysis. *Photo by Nathan Wang, Maxim Integrated, First Place Winner in Black & White Images, 2016 EDFAS Photo Contest.*

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PURPOSE: To provide a technical condensation of information of interest to electronic device failure analysis technicians, engineers, and managers.

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GUEST EDITORIAL

M&A IN FAILURE ANALYSIS

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Mergers and acquisitions (M&A) have been a significant part of the semiconductor industry for as long as I can remember, but they have grown in significance in the last few years, with the business community expecting more in the near future. M&A activity in the failure analysis (FA) segment of the semiconductor business has been a more recent development. Several years ago, the consolidation of FA contract laboratories was in full force. The economies of scale and the flexibility of being able to use multiple sites to improve cycle times, plus the ability to provide a wider range of services, were irresistible motivations to combine contract FA labs into a more national organization.

M&A activity among the tool providers seems to be exploding recently. The FEI acquisition of DCG merged two of the most significant manufacturers of FA tools into the biggest supplier to the FA community on a dollar basis. This was quickly followed by the acquisition of FEI by Thermo Fisher Scientific. All of this was a major event for the FA community. What are the implications of this business activity for tool users? Obviously, there can be short-term disruptions as the changes ripple through the FA community, but what are the long-term implications?

What are some of the benefits to the FA community? For users, the service base will ultimately become more local and more available. With cross-training on multiple tools, larger vendors eventually make service available more quickly on a worldwide basis. This has always been a major concern for smaller suppliers—where is service coming from? A larger service base will reduce the need to send in service from other areas of the world, thus reducing response times. Ultimately, this can also reduce travel costs for the manufacturer and impact service contract costs.

From an initial cost perspective, the larger company should be able to negotiate better prices on their components, with the expectation of passing along some of this benefit to their customers. Costs may be further reduced by the reuse of software across several applications. The larger companies are also more likely to have better manufacturing discipline. I have seen several small company manufacturing sites with less-than-ideal electrostatic discharge mitigation protocols. On the negative side, mergers result in a loss of jobs, impacting employees with whom the FA community is very comfortable.

Ultimately, does this provide the FA community with better tools? Does this kill the entrepreneurial spirit of the next potential tool developer? In much of technology, entrepreneurs often plan on being taken over by the major companies in order to go on to develop the next great thing. Entrepreneurs often lack the skills to optimally productize their ideas. There have been several examples of great FA tool ideas that failed due to a lack of business execution.

(continued on page 9)

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FAILURE ANALYSIS ON SOLDERED BALL GRID ARRAYS: PART II

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gert.vogel@siemens.com

INTRODUCTION

In the February 2017 issue of *EDFA* magazine, the failure analyis of soldered ball grid arrays (BGAs) with plane parallel removal of the BGA was discussed. In this second part, the analysis of voids in the BGA balls is continued, including case studies with plane parallel polishing of a printed circuit board assembly (PCBA).

TYPICAL ERROR PATTERN: LARGE VOIDS IN THE SOLDERED BGA BALLS

Large voids in BGA solder joints covering more than 30% of the ball area in the x-ray image (Fig. 1) are considered to be failures, in accordance with IPC-A-610, "Acceptability of Electronic Assemblies," and they result in the PCBA being rejected.

If the failure analysis shows indisputably that the failure was caused by a misalignment of the first inner layer, then it is possible to make a claim against the printed cirucit board (PCB) supplier. In our example, a metallographic cross section (Fig. 2, 3) was used to demonstrate this misalignment.

"BASED ON MANY CASE STUDIES, IT WAS SHOWN THAT FAILURE ANALYSIS ON SOLDERED BGAs ENCOMPASSES A WIDE FIELD. FAILURES CAN ORIGINATE IN MANY MANUFACTURING PROCESS STEPS."

It is not always possible to clearly identify the root cause, as in the above example. A cross section frequently shows only the voids but provides no evidence of the specific cause.

Sometimes, the previously mentioned preparation by polishing down the BGA allows the root cause to be determined, as shown in the next case study. Here, two eye-catching voids were seen during x-ray inspection (Fig. 4). For analysis, the specimen was first ground down to the center of the voids. This subsequently provided a cross section in the vertical axis for further analysis. Surprisingly, not only was a sharp-edged organic particle found in the

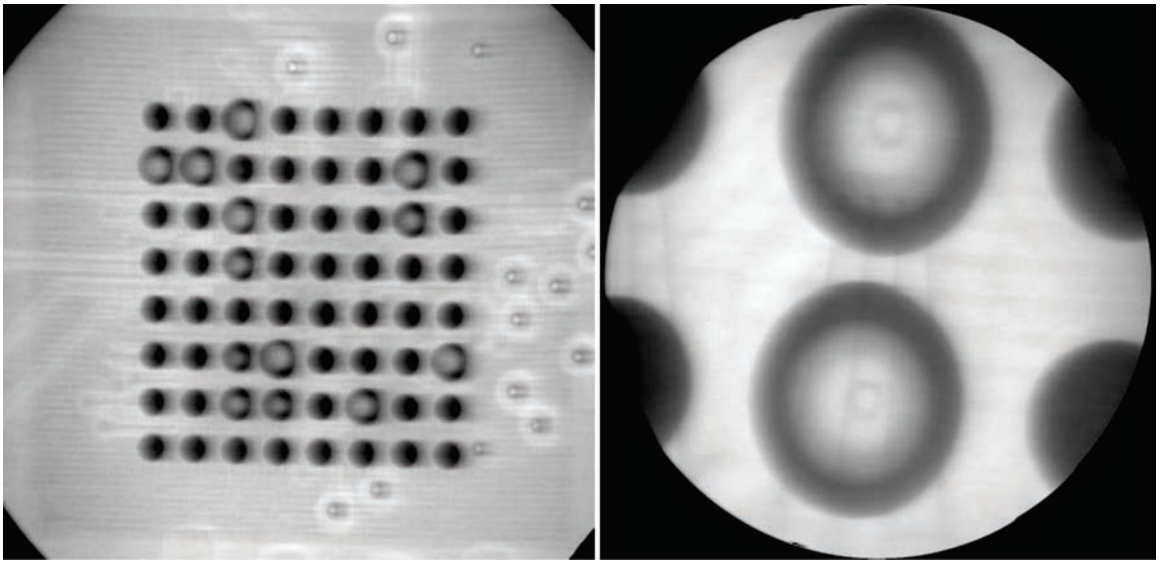

Fig. 1 **X-ray of a BGA with many large voids. The microvias can be seen at the center of the voids.**

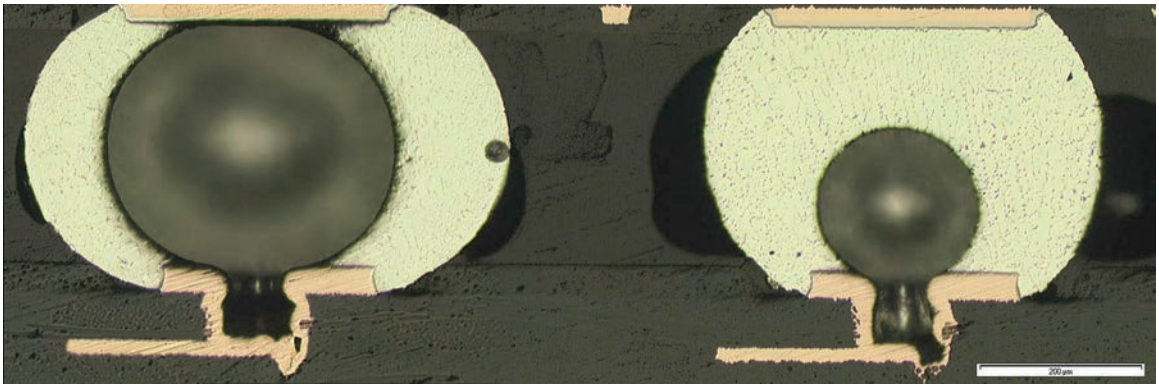

Fig. 2 **Cross section showing the failure: maladjustment of the microvias between the outer and the first inner layer**

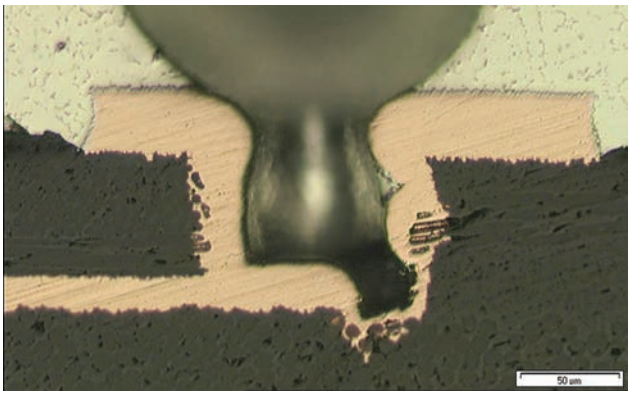

Fig. 3 **Cross section showing the root cause of the failure: misalignment between the microvia and the copper land of the first inner layer. The microvias are open to the resin of the PCB. Evaporating moisture from the PCB inflates the molten solder during reflow soldering.**

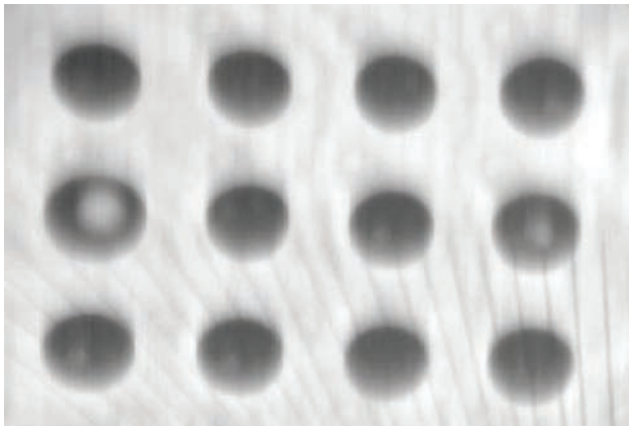

Fig. 4 **Another BGA after reflow soldering. X-ray analysis shows two voids.**

large void, but also an unobtrusive ball had dropped off the solder pad (Fig. 5). The root cause of the failure was now clear: A clogged stencil was again responsible, this time combined with a particle of the dried flux in the printed solder paste. The ball that had dropped off provided the indisputable evidence (Fig. 6). Performing only a cross section parallel or perpendicular to the BGA would

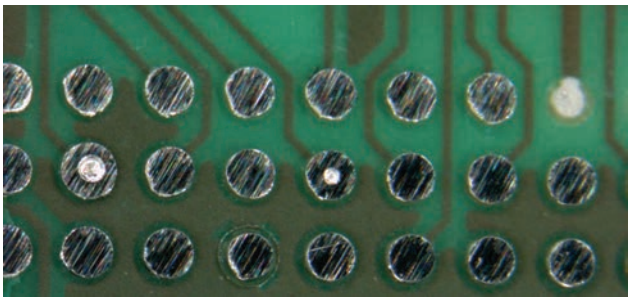

Fig. 5 **Plane parallel grinding of the BGA to the center of the voids. The large void on the left has an angular particle in it. This is dried flux from the solder paste that came off a stencil that had not been thoroughly cleaned. Surprisingly, one unobtrusive ball on the upper right dropped out.**

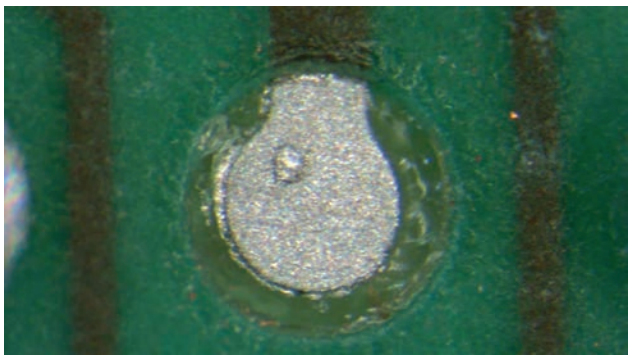

Fig. 6 **The footprint of the dropped-out ball shows that there was a problem with a clogged stencil mask while printing the solder paste. Just one small solder bead was transferred to the pad.**

not have provided sufficient evidence to indicate that a clogged stencil was the problem.

PLANE PARALLEL POLISHING DOWN OF A PCBA

If large voids are seen during x-ray analysis and there is suspicion that problems with microvias could be the reason for these voids, an alternative analysis method developed for this purpose is applied instead of the

standard cross section. The backside of the PCBA in the BGA area is polished down to just under the first inner layer of the PCB. Plane parallel polishing of several square centimeters of a PCB to an accuracy of ±10 µm in depth is assisted by the layered structure of the PCB. Grinding is stopped approximately 50 µm below the interesting first inner layer, and the plane is polished. Using polarized light, one can look through the rest of the resin and the glass fibers of the PCB (Fig. 7). In this case study, the inner layer is misaligned. All the microvias are open to the bulk of the PCB. In the cross section of Fig. 3, the misalignment is in the plane of the cross section. Figure 8 shows the more common situation: a misalignment under an angle of 45°. The image clearly shows that cross sections through such a copper pad under 90° or 180° would not provide indisputable evidence.

This is also valid for the "blowout" failure mode. In most cases, the holes in the copper sleeve of a through-hole are located at angles of 45° and therefore are hard to find with a cross section. If a section of a PCB with blowouts is heated in glycol to >100 °C, bubbles can be seen escaping from the through-holes. They primarily originate at an angle of 45° (Fig. 9). This is not by chance but depends on the alignment of the woven glass fibers in the PCB.

A misalignment of the microvias is not always the reason for an increased incidence of large voids in BGA solder joints. The next case study once again shows a row of big voids under x-ray inspection (Fig. 10). A cross section shows the voids, but no misalignment of microvias could be detected (Fig. 11). As before, the PCB was ground down underneath the microvias, and the bottom side of the first inner layer was viewed using polarized light (Fig. 12). This revealed that the inner copper layer had been perforated when lasering the microvias (Fig. 13). This information explains the appearance of the cross section of a perforated copper pad. Chemical desmearing of the microvia after lasering dissolved some of the PCB resin beneath the copper pad. After parallel cross sectioning, this gap looks

(continued on page 8)

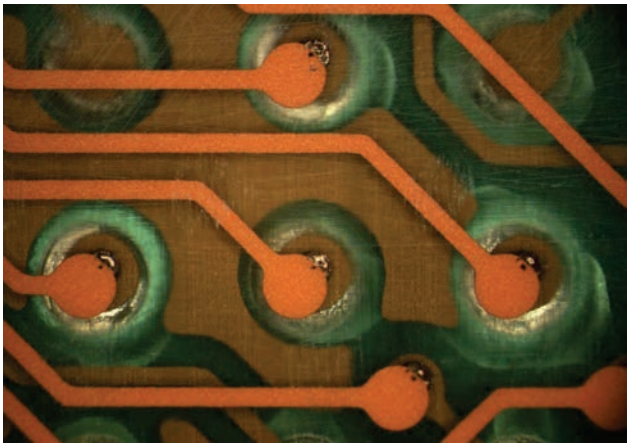

Fig. 7 **Plane parallel grinding of the PCBA from the backside to 50 µm below the first inner layer. The inner layer is misaligned. All microvias are open to the resin of the PCB.**

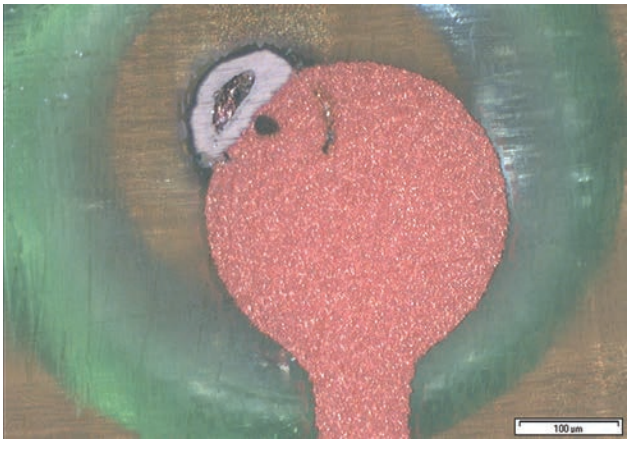

Fig. 8 **Magnified view of Fig. 7 showing detail of the misalignment**

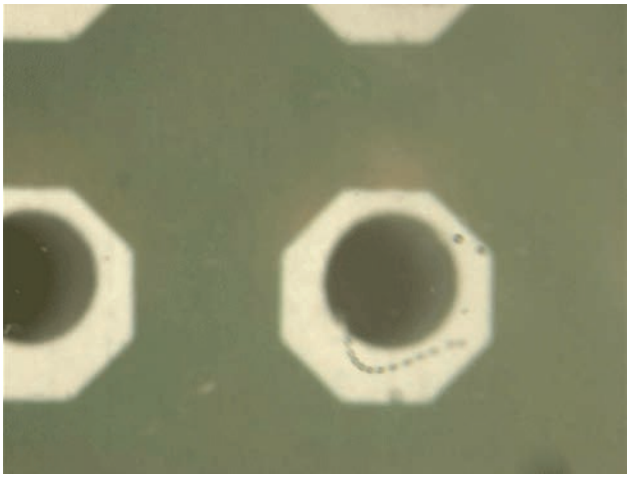

Fig. 9 **PCB with "blowout" failure pattern. Bubbles come out of a through-hole when heated in glycol. The location of the hole in the copper sleeve lies predominantly below 45° to the PCB alignment.**

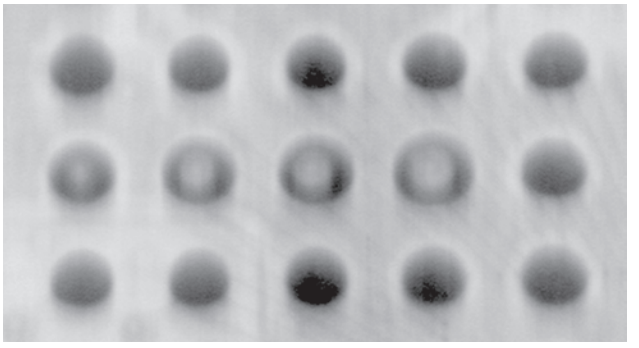

Fig. 10 **X-ray image of large voids in soldered BGA balls**

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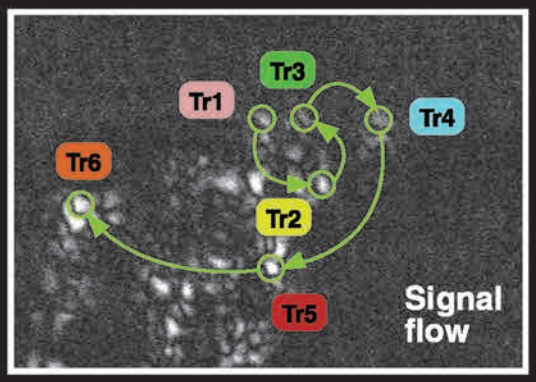
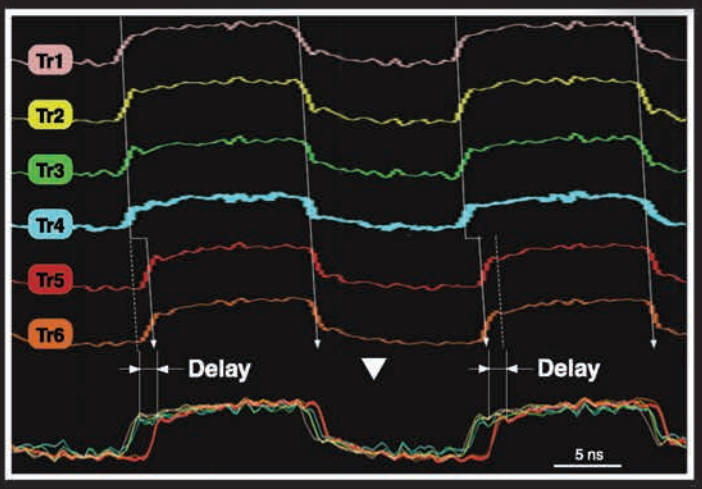


EOFM (electro-optical frequency mapping): This function captures images of nodes in isolated regions operating at a specific frequency. It makes it easier to observe whether or not the circuits are correctly switching.



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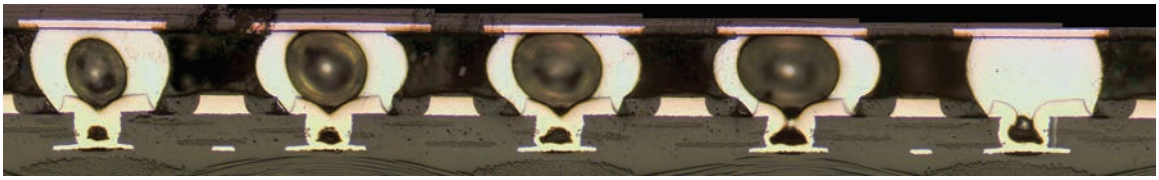

Fig. 11 **Cross section showing voids in the soldered BGA balls, but no misalignment is evident**

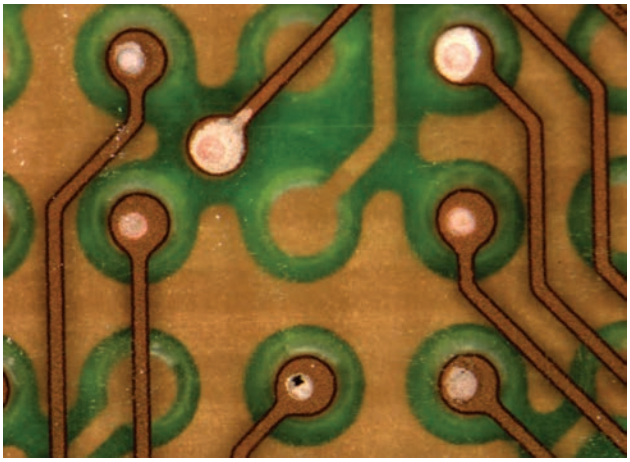

Fig. 12 **Grinding away the complete PCBA under the microvias shows that the inner copper layer had been perforated while lasering the microvias.**

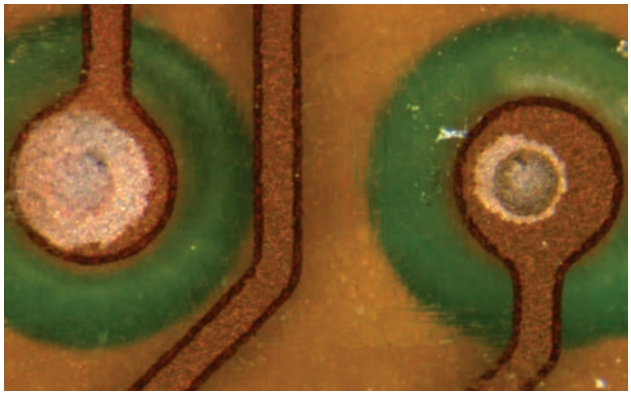

Fig. 13 **Perforated copper pads of the first inner layer viewed from below**

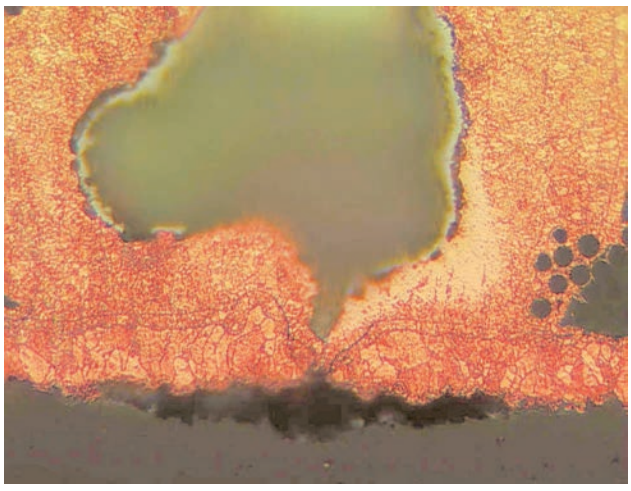

Fig. 14 **Cross section of a perforated copper pad. Chemical desmearing of the microvia after lasering dissolved some of the PCB resin beneath the copper pad. Under the microscope, this void looks like a silvery disk when viewed from below.**

like a silvery disk in the microscope when viewed from the backside. Copper deposition after the desmearing process is not always able to close the hole in the copper layer (Fig. 14). This means that some moisture from the PCB resin evaporates into the liquid solder ball during the reflow soldering process, which results in large voids that are identified during x-ray inspection. The supplier of the PCB confirmed that the laser had been replaced without subsequently calibrating the energy level.

SUMMARY

Based on many case studies, it was shown that failure analysis on soldered BGAs encompasses a wide range of possible failure mechanisms. Failures can originate in many manufacturing process steps. The stencil printing of the solder paste is often a critical process, but more often, faulty PCBs represent the root cause. However, defective silicon in the BGAs is extremely rare.

Making cross sections of soldered BGAs is a common approach when analyzing failures. Two new approaches were presented as additional methods for identifying the root causes of failures. Grinding away the corpus of the BGA while the soldered balls are still left on the PCB can provide insight into the failure mechanism. On the other hand, confirmation that all solder connections are perfect can indicate that there is a fault in the PCB layout. Grinding away the complete PCB from the backside until the base of the soldered balls can be viewed allows an electronic pathologist to check the quality and alignment of the microvias.

The combination of these methods with expert knowledge of all the various steps in the fabrication of PCBs and PCBAs can solve many problems in the production of electronic assemblies.

ABOUT THE AUTHOR

Gert Vogel studied physics in Stuttgart. He has been with Siemens for more than 30 years. Dr. Vogel was a semiconductor technologist in Siemens' DRAM production in Munich and Regensburg for seven years. He then moved to Siemens Amberg where, among other topics, he is a specialist in failure analysis of electronic components on printed circuit board assemblies. He led a tutorial, "Avoiding Flex Cracks in Ceramic Capacitors," at ESREF 2015. This was followed by a tutorial, "Creeping Corrosion of Copper on Printed Circuit Board Assemblies," at ESREF 2016.

NOTEWORTHY NEWS

IPFA 2017

The 24th International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA 2017) will be held **July 4 to 7, 2017,** at the Intercontinental Chengdu Global Center, Chengdu, China. The event will be devoted to the fundamental understanding of the physical mechanisms governing failure in a large variety of advanced semiconductor devices and the electrical/physical failure analysis techniques, methodologies, and tools used to reliably identify root-cause failure in these devices.

IPFA 2017 is organized by the IEEE Reliability/CPMT/ED Singapore Chapter, IEEE Electron Devices Society Chengdu Chapter, and the University of Electronic Science and Technology of China. The Symposium is technically co-sponsored by the IEEE Electron Device Society and IEEE Reliability Society.

For more information, visit the IPFA website at ipfa2017.com/.

GUEST EDITORIAL

CONTINUED FROM PAGE 2

On the negative side, this can lead to monopolistic traits. Prices can be high when there is only one source. Also, the FA community is very good at feature creep. Feature creep is often dealt with better by larger companies, but they are also very adept at adding costly extra features to their products.

There is also a good chance that the larger companies will earn higher profits. This is clearly good for the big company, but does it also provide a benefit to our community? It can provide an opportunity for more investments in new tools or applications. Small companies with a single idea achieve success or go bust based on that idea. A large company can accept a relatively small loss on a promising concept, while the same loss will drive a small company out of business. However, to offset the costs of monopolistic suppliers, we can hope that much of the increased profit will be reinvested into tool improvements. Speculative investments in tool development can be made with adequate funding without risk to the company's existence. It also makes it possible for the bigger companies to be able to fund additional acquisitions of promising FA technologies developed by entrepreneurs.

While there are obviously monopolistic issues with some of the major M&A activity in FA tools, there are equally as many advantages. Bigger companies can provide better service in terms of cycle time and parts inventory. They can provide better quality and reliability based on better manufacturing controls. They can also provide adequate funding for new technologies, both internally and through acquisitions of startups.

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POSITRON BEAMS AS EFFECTIVE NONDESTRUCTIVE ANALYSIS TOOLS FOR THE SEMICONDUCTOR INDUSTRY

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INTRODUCTION

Slow positron beam spectroscopies are capable of revealing information about the arrangement of dopants and defects in a metal or semiconductor sample with a resolution better than a single atomic lattice site at depths typically up to a few micrometers. Information on this scale at depths more than a few monolayers cannot be achieved by any other spectroscopic technique. Figure 1 shows a comparison of techniques. Furthermore, the sensitivity range for open-volume defects starts at approximately one vacancy per 10^7 atoms. This enormous sensitivity comes about because a thermal positron can diffuse approximately 100 nm in the bulk of a material, and so each can probe a large number of lattice sites. Furthermore, positrons annihilate with only the easily replaced electrons, making positron spectroscopies nondestructive. The slow positron beam is a uniquely useful tool when it comes to characterizing and evaluating semiconductors.

"POSITRONS TEND TO BECOME TRAPPED IN REGIONS OF HIGH ELECTRONEGATIVITY, SUCH AS IN DISLOCATIONS, VACANCIES, OR AROUND SOME TYPES OF IMPURITIES IN THE SAMPLE."

The positron is the antimatter partner of the electron; it is identical but with a positive charge. When a positron

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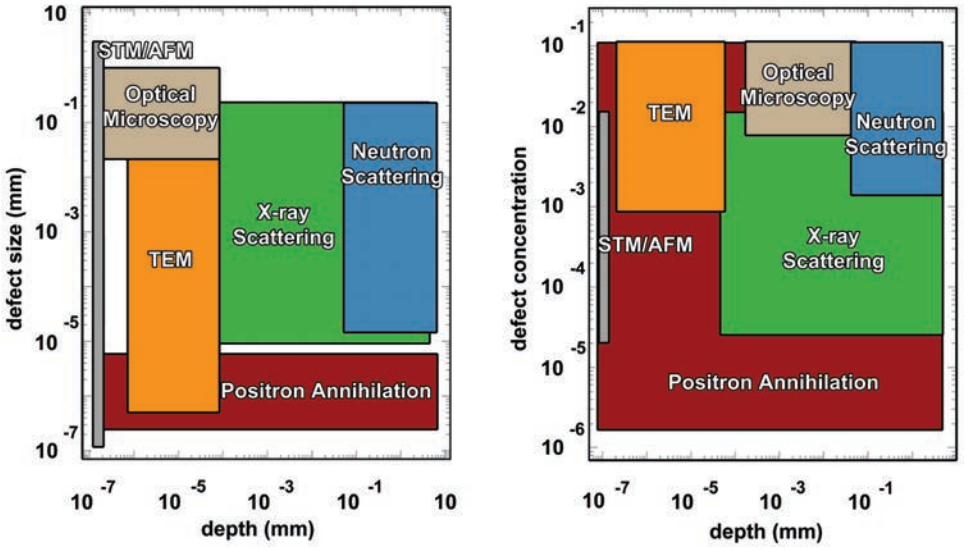

Fig. 1 **Comparison of the capabilities of spectroscopic techniques. Positrons are capable of discerning defects smaller than an atom and can penetrate deeply into a sample.**

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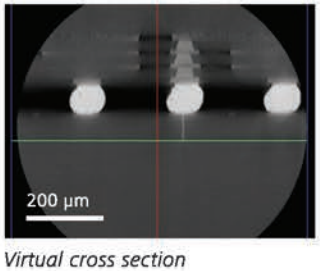
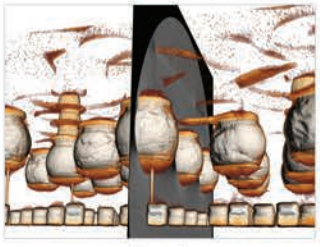


Virtual cross section



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POSITRON BEAMS AS EFFECTIVE NONDESTRUCTIVE ANALYSIS TOOLS

(continued from page 10)

encounters an electron, they annihilate. Approximately 99.7% of such collisions result in the emission of two 511 keV (kiloelectron volts) photons back-to-back in the frame of reference of that collision.[1] Deviation from linearity of the photons in the laboratory frame arises primarily from the momentum of the electron, and this was first used to measure the Fermi surfaces of metals and alloys.[2]

The difference in charge of the positron from that of the electron creates a number of important differences in its interactions with matter. Positrons tend to become trapped in regions of high electronegativity, such as in dislocations, vacancies, or around some types of impurities in the sample. Additionally, the photoelectric work function can be negative for surfaces of some materials. For electrons, a material's work function (ϕ_-) is always positive; energy must be put into the electrons to free them from the surface. For positrons, however, the surface dipole potential (D) in the work function has the opposite sign of the bulk chemical potential (μ), and so the positron work function (ϕ_+) is very nearly zero and may be negative according to:[3]

$$\phi_- = +D - \mu_-$$

$$\phi_+ = -D - \mu_+$$

If a positron inside the bulk of the material reaches such a surface, it will be ejected from the sample, picking up the work function energy. This is the mechanism behind positron moderation, which allows the creation of monoenergetic positron beams. Unfortunately, it is a highly inefficient process.

Positrons penetrate a sample to an average depth that depends on their energy. A beam of a few electron volts samples only the first monolayer of the sample, whereas a positron in a beam of 35 keV can penetrate to a depth of 10 μm. This allows for depth-dependent characterization of defects in a sample.[4]

Positrons in slow positron beams originate from either pair production or radioactive decay. Pair production techniques require either an accelerator, such as the Elbe Positron Source in Dresden, Germany, or a nuclear reactor, such as the Neutron-Induced Positron Source at Munich (NEPOMUC). These systems allow for the creation of positron beams of incredible intensity ($3 \cdot 10^9$ moderated positrons per second in the case of NEPOMUC), limited only by the count rate of the detectors or, in some cases, the capability of components of the beam to dissipate heat.[5] Unfortunately, all of these systems also require large facilities and thus must compete for resources with other projects and suffer the facilities' downtimes. This makes them expensive and unsuitable for extensive industrial use. Traditional source-based positron beams are relatively inexpensive to build and operate and can be constructed anywhere, because they only use a portable radioactive sample. However, they are limited by low positron count rates, and that translates to longer measurement times, which has limited their application

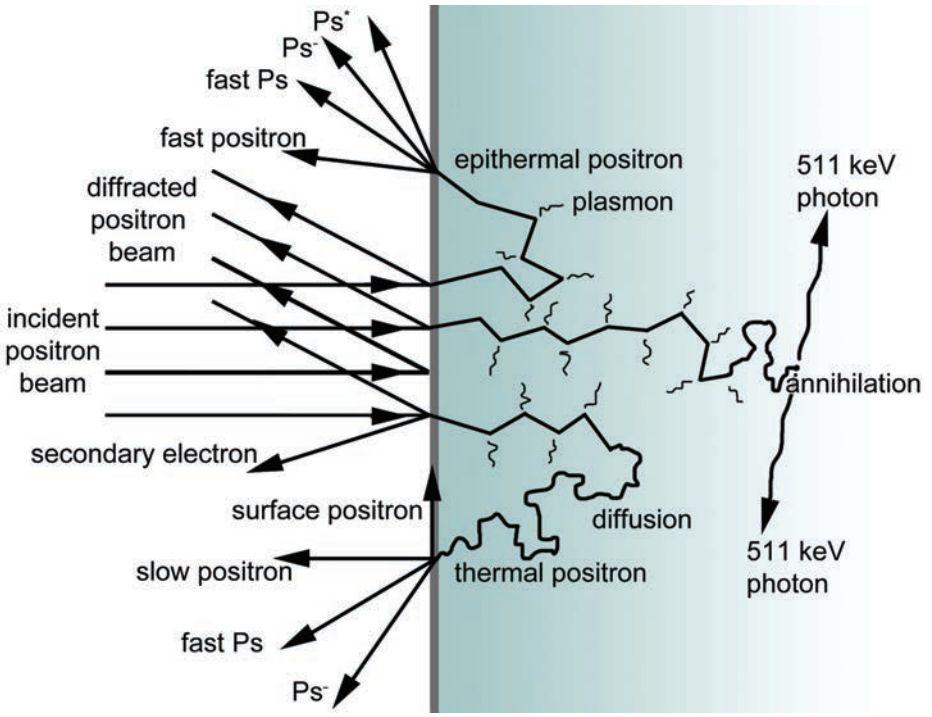

Fig. 2 **The multitude of possible interactions between a positron (Ps) beam and a metal or semiconductor target**

in industry. One significant source of limitation is the inefficiency in the moderation process; the other lies in the sources commercially available. The deflection focusing positron gun (DFPG) developed at The University of Texas addresses both of these limitations.

The DFPG has been designed to generate the most intense source-based slow positron beams. Positrons are created in a large ring of radioactive material. This source geometry dramatically increases the number of positrons generated by simply increasing the surface area of the source that is contributing positrons to the beam. Secondly, the DFPG uses advances in moderator geometries to more efficiently produce moderated positrons. The geometry of the DFPG also suppresses background counts by greatly reducing the number of unmoderated positrons leaving the gun.

POSITRON INTERACTIONS IN MATTER

Positrons are the antimatter partner of the electron. The two particles have the same mass, but the positron has an opposite charge. When slow positrons—those with less than a few megaelectron volts—encounter a metal or semiconductor, three categories of outcomes are possible: reflection, absorption and re-emission, and annihilation, as depicted in Fig. 2.

A fraction of the positrons in a beam will be scattered elastically when they encounter a surface. More positrons are diffracted in this way when the beam energy is lower. Measurement techniques such as low-energy positron diffraction can use these diffracted positrons to develop an interference pattern, which relays information about the arrangement of the atoms at the surface of a metal or semiconductor.[6]

Positrons penetrate to an average depth that increases with their initial kinetic energy. During this process, the positrons undergo repeated inelastic deflections, losing energy primarily through the creation of phonons and plasmons. The implantation depths for a given positron kinetic energy have a Makhovian profile.[7] An example of implantation profiles for varying energies is shown in Fig. 3.

Positrons lose energy via inelastic collisions until they have thermalized with the material. Some may arrive at a surface before they have fully thermalized; otherwise, they diffuse through the material with an energy of kT until they annihilate with an electron or arrive at a surface.

A number of things can happen when a positron arrives at the surface. If the surface has a positive work function greater than the positron's energy, the positron may become trapped there. If the positron has enough energy to escape, it may be emitted as an epithermal positron, or it may pick up an electron from the surface and escape as neutral, atomlike positronium. If the positronic work function ϕ_+ is negative, a thermalized positron may be emitted with an energy of $kT + \phi_+$, allowing for the creation of monoenergetic positron beams.

Positrons that do not end up back at the surface are annihilated in the interior of the sample. Positrons in a material have a diffusion length that is determined by the material itself and its configuration. In a perfect crystal lattice, this length is usually approximately 150 nm. Lattice defects with regions of high local negative charge, such as dislocations, vacancies, and near-certain impurities, can trap positrons. In this case, their diffusion length is diminished, but their lifetime is extended. Different types of defects are associated with distinct lifetimes, which can even be used to distinguish between different arrangements of the same type of defect. For example, one can determine if dopants tend to exist as single atoms, in pairs, or in larger clusters, and in what ratios.

Positrons remaining in a sample eventually find an electron and are annihilated. There are a number of channels for this reaction to proceed down, but 99.7% of the reactions result in the emission of two photons back-to-back in the frame of the interaction. Each photon has an energy very close to the mass energy of the electron or positron: 511 keV. Because the electrons in the sample are moving, there may be a difference between the reference frame of the interaction and that of the lab frame of several electron volts. Tightly bound core-shell electrons move much faster than outer-shell or conduction band electrons and therefore show a greater difference from the lab frame. This appears either as an increasing opening angle when the moment difference is more transverse to the direction of flight of the photons or as a greater

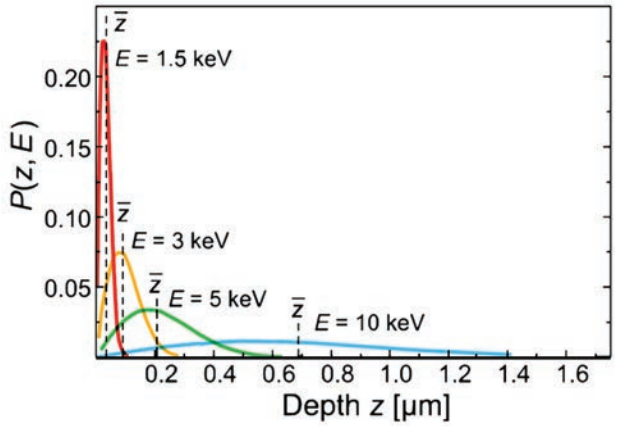

Fig. 3 Makhovian implantation profiles in single-crystal silicon. Source: Ref 8

Doppler shift when more in-line. Positron spectroscopies have been developed to examine each of these cases.

POSITRON SOURCES

Table 1 lists a number of radioactive sources used to create positrons for slow positron beams. Virtually all source-based beams use commercially available ^{22}Na capsules. ^{22}Na has a long half-life, which means that the capsule does not need to be replaced more than every few years, and its high positron fraction helps mitigate the lower count rate. A few other details are worth noting. ^{11}C is often used in medicine because it has such a short half-life. ^{58}Co can be made by irradiating nickel in a reactor, and it has an acceptable lifetime.[9] It has been chosen as the source for use with the experiments discussed subsequently. ^{64}Cu is another commonly created test source, because it can easily be made with access to a nuclear reactor, and it decays quickly.

A positron is created when a proton decays into a neutron, a neutrino, and a positron. Because this is a three-body decay, the positrons are created with an energy spectrum determined by the decaying atom. All have a similar shape, as shown in Fig. 4. The endpoint energy represents the highest-energy positron that can be created from such a decay, but it is the energies near the peak intensity that are important. These are the positrons that will be slowed to make the bulk of the beam. Another significant detail from Fig. 4 is the positron fraction. This represents the number of radioactive decays that will result in creation of a positron. For atoms such as ^{22}Na, which has a positron fraction of 0.91, most decays result in a positron, but for ^{64}Cu, less than one-fifth of all decays generate one. Furthermore, the half-life determines how frequently the element decays and therefore how often positrons will be generated.

Table 1 Various radioactive sources used for positron production

Source	Endpoint, MeV	Production	Half-life	Positron fraction
^{11}C	960	^{11}B (p, n)	20 minutes	0.99
^{22}Na	540	^{24}Mg (d,α)	2.6 years	0.91
^{58}Co	470	^{58}Ni (n, p)	71 days	0.15
^{64}Cu	650	^{63}Cu + n	12.8 hours	0.19
^{66}Ge	1880	^{66}Zn (α, 2n)	275 days	0.86

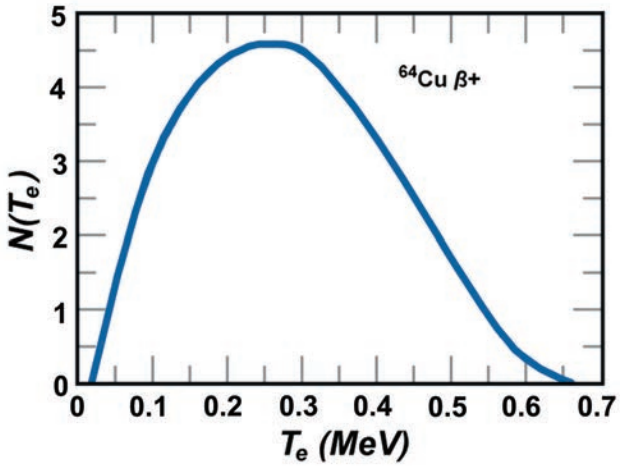

Fig. 4 Intensity distribution of positrons emitted by ^{64}Cu. Source: Ref 10

Source geometry also plays an important role in generating positrons, and it comes with some strict limitations. The first is the thickness of the source. A thicker source contains more radioactive material and thus will generate more positrons. However, as the source is made thicker, fewer and fewer positrons are energetic enough to penetrate through to the source itself to contribute to the beam count. The benefit of increasing the thickness of the source diminishes until the absolute limit is reached, when positrons generated farthest back all annihilate inside the source itself. Positrons generated from a broad source run afoul of the Liouville theorem when one attempts to use electrostatic forces to focus them into a tight beam. The Liouville theorem says that phase space is conserved when conservative forces are involved. A tight beam of particles traveling parallel to one another cannot be created from a broader beam by using only conservative processes, such as electrostatic forces. One may focus such a beam into a smaller region at the cost of it being a parallel beam. Having a small parallel beam is important, however, because the detectors must be placed far from the source of the positrons, which necessitates beam transport for a meter or more.

In the DFPG, the source is designed as a large ring structure. This maximizes surface area while maintaining a symmetry that allows the monoenergetic positrons to be focused to a single point. At that point, a nonconservative process is introduced to reorient the positrons into a parallel beam.

MODERATION

The most significant limitation to positron beam intensity lies in the moderation step. Positrons emerge from a radioactive source with a spectrum of energies. To obtain an acceptable resolution, the positron beam must have a

(continued on page 16)

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POSITRON BEAMS AS EFFECTIVE NONDESTRUCTIVE ANALYSIS TOOLS *(continued from page 14)*

uniform energy. Positrons either pass through a moderator (transmission) or penetrate into and then are re-emitted from the same surface (reflection). Positrons with energies allowed by nuclear decay primarily lose energy via inelastic collisions until they reach thermal equilibrium with the material. Once thermalized, a positron diffuses through the moderator. If a positron finds the surface of the material, it is ejected perpendicular to that surface with only the work function energy. Otherwise, it will eventually annihilate with an electron. There is a characteristic diffusion length associated with each material. This is the average distance that a positron will travel through a pure, defect-free sample. Lower-energy positrons may thermalize too far from the emitting surface, and higher-energy positrons may reach the surface before they have thermalized and leave with their energy plus the contribution from the positronic work function. There is an ideal moderator thickness that depends on the spectrum of positron energies and the type of moderator.

Even under ideal circumstances, this thickness can only be chosen to moderate a small region of the positron energy spectrum. Positrons of higher energy are not fully moderated, and positrons of lower energy thermalize too far from the emitting surface and annihilate within the moderator. Because of this limitation, the primary limitation on the intensity of positron beams lies in their moderation. Table 2 lists many common moderators. Moderation efficiencies less than 10^{-4} tend to struggle with breaching. The most common moderator, tungsten, has a moderation efficiency of 10^{-3}, which is relatively good, and it is the most stable when exposed to air, retaining over 60% of its moderation efficiency.[11] Slightly higher efficiencies can be obtained by using some solid noble gas moderators, but they are much more difficult to handle.

Virtually all tungsten moderators in use are foils. The optimal thickness for a tungsten foil moderator when used in combination with ^{22}Na is 1.8 μm. However, only 9 μm is commercially available. Efforts to uniformly etch or flash lamp anneal these tungsten foils run into difficulty due to 25% variance in thickness.[17] Annealing is important to eliminate defects in the moderator that may trap thermalized positrons and prevent them from reaching the surface.

One strategy is to increase the useable moderator surface area through the use of moderator meshes. A stack of tungsten meshes would increase the percent of volume within one positron diffusion length, allowing more thermalized positrons to escape. Epithermal positrons would be capable of penetrating into additional wires and losing energy until they too become thermalized. It is estimated that this could improve moderator efficiency by an order of magnitude.[18]

Work by the authors' group has shown that tungsten meshes can be etched slowly and with incredible precision by using a dilute solution of sodium hypochlorite. The meshes are commercially available as 25-μm-diameter wires spaced two per millimeter. This wire thickness is well above optimum, but the authors have shown that wire integrity down to 8.45 μm diameter thickness can be maintained even as more than 80% of the mass is removed, as shown in Fig. 5.

Table 2 Assortment of moderators

Moderator	Efficiency	Energy spread, eV	Reference
Cu (110) with S	10^{-3}	0.40	12
Pt with MgO	10^{-5}	1.20	13
Au	10^{-4}	0.30	14
W (110)	10^{-3}	1.5	15
Al	10^{-5}	0.15	16

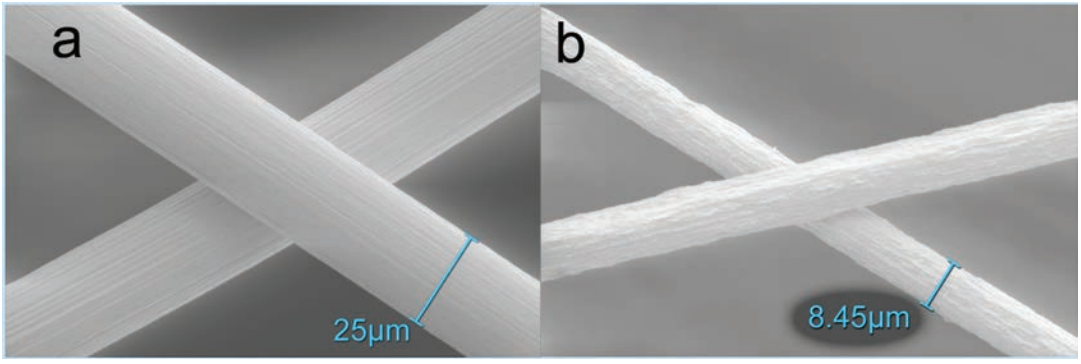

Fig. 5 (a) Tungsten mesh as-received. (b) Tungsten mesh after etching in sodium hypochlorite. Note that the wire integrity is still intact even though most of the tungsten has been etched away.

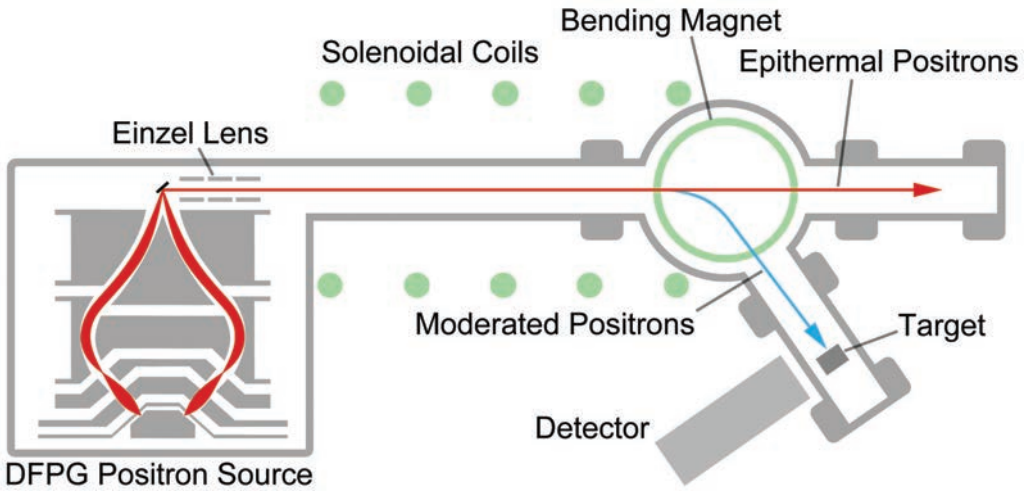

Fig. 6 **Beam line used for the deflection focusing positron gun**

BEAM TRANSPORT

The transport of the monoenergetic beam is nearly completely lossless. Figure 6 shows the arrangement of the beam. The beam is directed through a vacuum of 10^{-6} torr or less and is guided by toroidal magnets that keep the beam collimated for the meter or more distance in spite of small transverse momenta. There is also a Helmholtz coil, which is necessary to cancel the effects of the magnetic field of the Earth. Magnets are used to bend the moderated beam to send it on a different trajectory. Positrons that are unmoderated or only partially moderated have a larger turning radius than positrons that are moderated. When the moderated beams go around the bend, the others are instead directed toward a shielded beam dump. The beam is then passed through an electrostatic voltage drop, which accelerates the positrons. This drop can be varied to alter the energy of the positrons in the beam and thus their penetration depth. The beam finally passes through an aperture to remove fringe positrons, thus forming a tight beam that strikes the target sample. The target sits at least a meter from the source to reduce background radiation at the detectors.

DEFLECTION FOCUSING POSITRON GUN

The problem of increasing the intensity of the slow positron beam has been addressed with the development of the DFPG. This device uses advancements in moderator mesh technology, in combination with a much larger source ring, and a second moderation step to produce a collimated beam similar to those created from traditional ^{22}Na sources, only with a greater intensity. Figure 7 shows the diagram for the device.

Instead of the standard small source (2 mm diameter), the DFPG uses a ring-structure arrangement to increase the amount of source that is available to the beam by 2 orders of magnitude. Directly above the source is the moderator, which consists of layered tungsten meshes. This is collectively held at 5 kV and is labeled "1" in Fig. 7. The voltage difference between the source and the extraction lens draws the emitted positrons forward from the meshes, as shown in Fig. 8.

Once the positrons are emitted from the moderator meshes, they enter the focusing layers of the DFPG. The next three stages constitute a modified Einzel lens, labeled "2" in Fig. 7. The first and last stages (2a and 2c) are held at 0 V. The large voltage difference between the source and the first stage of the lens (2a) pulls the moderated positrons forward to form a beam. The center stage of the

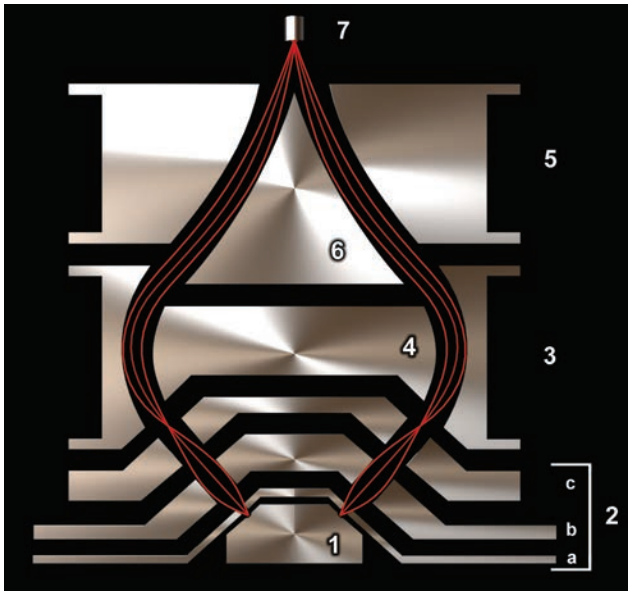

Fig. 7 **Deflection focusing positron gun shown in cross-sectional profile, with the individual parts numbered for reference. The beam path is outlined in red.**

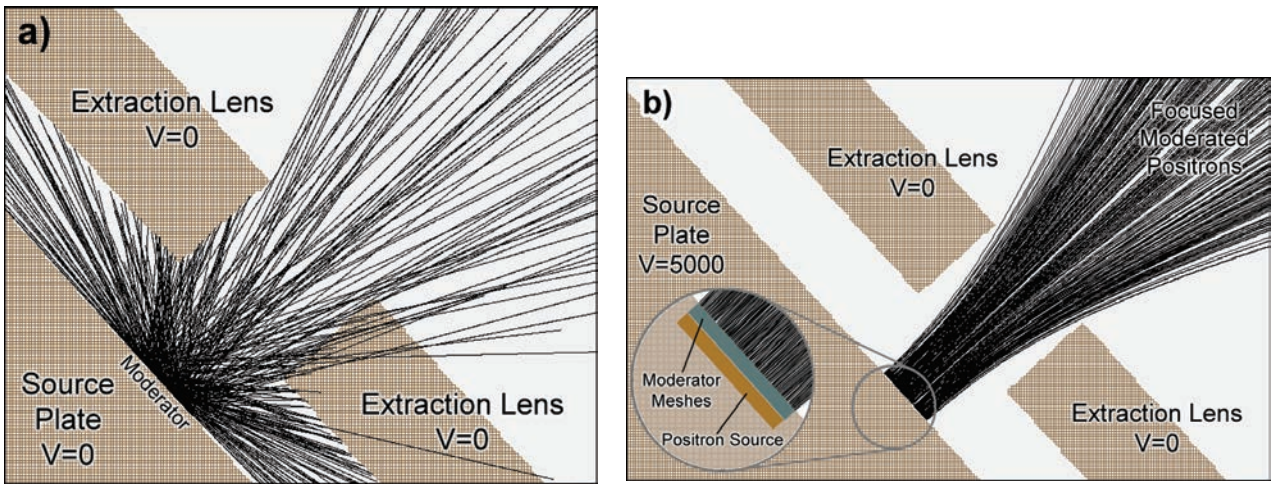

Fig. 8 **Efficiency of the collection optics. (a) Uniform distribution of positron emission when there is no voltage difference between the source and the extraction lens. (b) 100% collection efficiency when the source is biased at 5 kV against the extraction lens**

lens is held at 3.8 kV (2b), which defocuses the beam so that it can be refocused by the final stage of the lens (2c).

The focused beam enters the hollow spherical region, which bends the beam to refocus it to a single point. The outside of the region (labeled "3") is held at 2.3 kV, which guides the beam around the bend. The inside spherical electrode (labeled "4") is held at 0 V. The conical region guides the ring-shaped beam to a single point, where it strikes a second moderator. The outside of it (labeled "5") is held at 0 V, while the inside is at 780 V.

Finally, the beam strikes a second moderator (labeled "7"), which has a distinct purpose from the first. Undergoing two moderation steps with an efficiency of 10^{-4} would severely detrimentally affect the intensity of the beam; however, this is not what happens. For the first moderation step, the positrons in a small segment of the spectrum of positron energies are reduced to thermal energies. In the second moderation, only a small nonconservative process is introduced to a beam with uniform energy to overcome phase space limitations imposed by Liouville's theorem that would prevent these positrons from being focused into a collimated beam. The re-emitted positrons then travel as a tightly focused parallel beam. The second moderator is reflection based.[19]

MODERN POSITRON SPECTROSCOPIES

Crystal imperfections trap positrons differently depending on the nature of the imperfection; there are two categories of slow positron beam spectroscopies capable of analyzing those differences. The first category, positron lifetime spectroscopy, measures the length of time between a positron entering the sample and annihilating with an electron. The lifetime of a positron in a solid depends inversely on the local electron density. Different types of defects have unique positron lifetimes that differ from the lifetime of the positron in the bulk of the material. A vacancy in the crystal lattice traps positrons, because the lack of a nearby nucleus increases the negative charge density in the area and becomes a positron trap. While the region has a greater local negative charge, there are actually fewer electrons there because of the absence of core-shell electrons around the nucleus. This leads to a longer lifetime for trapped positrons. The number of different lifetimes measured and their relative intensities give information about the types and relative abundances of a variety of defects. Positron lifetime spectroscopy requires a start signal for the creation of each positron and a stop signal for each annihilation. The most straightforward method is to use an intermittent or pulsed beam. For positrons created in pulsed bunches in an accelerator, lifetime spectroscopy is ideal. When using a radioactive source to generate the beam, however, one must chop and bunch the continuous supply of monoenergetic positrons.

The other main category of slow positron beam techniques measures the positron's momentum. Positrons penetrate a sample material to a mean depth proportional to their energy. They lose energy by undergoing inelastic collisions until they thermalize to a Maxwell-Boltzmann distribution, that of a classical gas. The thermalized positrons then diffuse through the material until they annihilate with an electron. This annihilation releases two 511 keV photons back-to-back in the reference frame, where their net momenta are zero. Because the electrons in the sample are moving much faster than the positrons, that reference frame is likely to be moving relative to the laboratory. In early experiments, the difference in

momenta between the lab frame and the annihilation frame was measured by finding the opening angle of the emitted photons. Detectors were placed several meters to either side of the sample at angles varying from 180°. This is called angular correlation of annihilation radiation (ACAR). Increasingly shallower angles measure an increasing momentum difference between the zero momentum frame and the lab frame transverse to the direction of travel of the emitted photons. The major drawback of ACAR is extremely low count rates; this is due to the small solid angle of the detector, which is a long distance from the sample being studied. For this reason, Doppler-broadening spectroscopic techniques are now used. One measures the momentum difference in-line with the emitted photons. In this case, one photon will have more energy and appear blue-shifted due to the electron's original momentum in that direction, and the photon moving in the opposite direction will be red-shifted symmetrically about the 511 keV peak. The detector can be placed right beside the sample, which increases the detection rate by orders of magnitude. Using two detectors, the photons can be observed in coincidence, and background detections can be dramatically reduced.

A number of detectors are placed as physically close to the target as possible. The configuration of these detectors varies depending on their purpose. Typically, at least one cryogenically cooled high-purity germanium (HPGe) detector is used because of its high energy resolution, and often it is paired with another HPGe, or with a NaI(Tl) or BaF_2 detector. The HPGe detectors have an energy resolution of approximately 2.4 eV at 511 keV, and they are absolutely necessary for Doppler-broadening spectroscopies. The NaI(Tl) and BaF_2 detectors have a lower energy resolution but a higher efficiency, and they work well with time-of-flight measurements or as coincidence counters.

CONCLUSION

Positron spectroscopies offer a level of precision for defect detection and identification not available for any other spectroscopic technique. Unfortunately, traditional positron beams have a lower intensity than is viable for time-sensitive commercial uses. To make the positron beam a more useful tool for the semiconductor industry, the DFPG has been developed, which increases the intensity of a traditional beam through a number of approaches.

An intense source of positrons for a beam can be created by using a combination of a larger source, precisely etched moderator meshes, and an electrostatic lensing system. It is designed to image moderated positrons emitted from a thin, ring-shaped source. The size and shape of the source allows for a larger amount of radioactive material and therefore more positrons while minimizing self-absorption and thermal breakdown. The positrons emitted by the radioactive isotopes are focused by the DFPG into a small spot of only a few millimeters.

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NOTEWORTHY NEWS

MICROSCOPY & MICROANALYSIS 2017 MEETING

The Microscopy & Microanalysis (M&M) 2017 meeting will be held **Aug. 6 to 10, 2017,** in St. Louis, MO, with a theme of "Anniversaries." The Scientific Program features the latest advances in the biological, physical, and analytical sciences as well as techniques and instrumentation along with special anniversary lectures. A special symposium will celebrate 50 years of atom probe tomography. Complementing the program is one of the largest exhibitions of microscopy and microanalysis instrumentation and resources in the world. Educational opportunities include a variety of Sunday short courses, tutorials, evening vendor tutorials, pre-meeting workshops, and in-week intensive workshops. The opening reception offers an opportunity to meet new people in the field and renew old acquaintances, and the Monday morning Plenary Session features showcase talks from outstanding researchers as well as recognition of the major Society and Meeting award winners. There will be other important awards conferred during the meeting, including daily poster awards to highlight the best student posters in instrumentation and techniques as well as biological and physical applications of microscopy and microanalysis.

M&M is co-sponsored by the Microscopy Society of America and the Microanalysis Society and, for the first time, by the International Field Emission Society. For more information, visit microscopy.org/MandM/2017.

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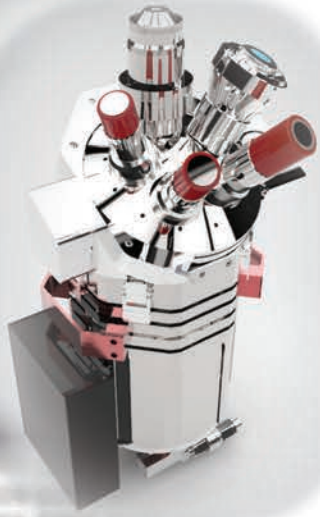

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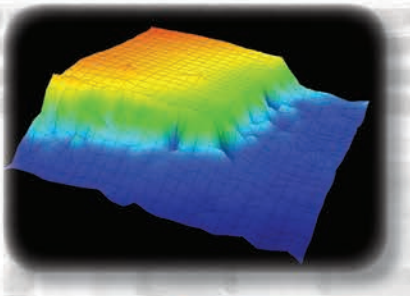

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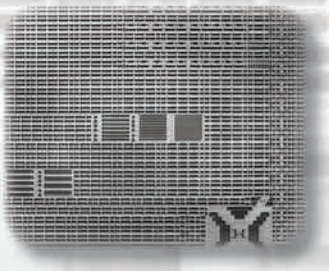

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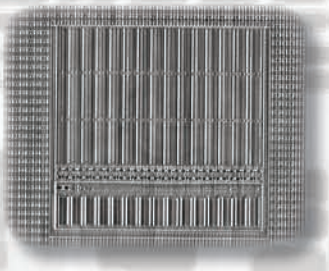

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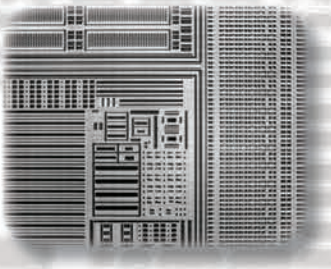

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ADVANTAGES AND CHALLENGES OF 3-D ATOM PROBE TOMOGRAPHY CHARACTERIZATION OF FinFETs

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INTRODUCTION

Atom probe tomography (APT) is a three-dimensional (3-D) characterization technique that is rapidly expanding its area of influence from primarily metals to include a plethora of fields ranging from semiconductor devices and thin films[1-3] to bulk oxides[4] and geological sciences (including meteorites!)[5] and even to biological materials.[6] Due to its unique nature, APT thrives at producing first-of-a-kind analysis, assisting in development of new materials or structures, and identifying material response to external forces.[7] Atom probe tomography is of high interest due to its capability to provide both structural and chemical analysis of buried features from any desired perspective with subnanometer resolution[8,9] and all within the same volume. This is particularly advantageous when complex 3-D features cloud one's ability to provide the necessary analysis using other analytical techniques or when advanced modeling is required for proper interpretation. Examples of such situations include quantum dot dissociation,[10] nanocluster/nanoparticle formation,[11] dissolution of alloy or dopant constituents at dislocations and grain boundaries,[7] and dopant distributions in 3-D semiconductor devices.[1,3] These advantages of APT make it a powerful tool for failure analysis and research and development of the next-generation technologies.

Atom probe tomography is a destructive technique that relies on charge concentration at a sharp point to field evaporate atoms from a conical-shaped sample. The collected atoms are then reconstructed into their original positions using a computer algorithm making use of a position-sensitive detector and time-of-flight measurements. The nature of the data collection and the digital reconstruction are what provide the unique 3-D capabilities. Once accurately reconstructed, buried nanofeatures can be isolated and examined from any and every angle. Atomic profiles can be measured throughout layers or across interfaces. Trace contaminant or dopant profiles can be mapped. Various films or materials can be highlighted for clearer visualization. Various isotope ratios can be measured. These examples exhibit the power of 3-D APT and demonstrate why it is quickly growing in popularity in a large number of fields. This article discusses the basics of APT sample preparation, data collection, and analysis by looking at a case study focused on state-of-the-art fin-shaped field-effect transistors (FinFETs).

"ATOM PROBE TOMOGRAPHY IS OF HIGH INTEREST DUE TO ITS CAPABILITY TO PROVIDE BOTH STRUCTURAL AND CHEMICAL ANALYSIS OF BURIED FEATURES FROM ANY DESIRED PERSPECTIVE WITH SUBNANOMETER RESOLUTION."

THE MAKING OF AN APT TIP

Typical APT sample preparation follows a similar procedure to that proposed by Thompson et al.,[12] where an initial lamella is pulled in a similar fashion to transmission electron microscopy (TEM) sample preparation. Sections of the wedge-shaped lamella (Fig. 1a) are then cut and welded to narrow posts, where each section is prepared into a separate APT tip. A focused ion beam (FIB) is used to create the conical tip in a series of concentric milling steps, where the center of the milling pattern is blanked to protect the final area of interest.[13] With each step, the diameter of the blanket portion of the pattern is shrunk, and the FIB voltage and/or current can be gradually decreased to reduce damage to the area of interest. The final shape of the sample is generally comparable to that of a sharpened pencil, such as the tip shown in Fig. 1(b). The finished tip has a topmost diameter of 20 to 100 nm

and should have a well-defined, uniform shank angle and smooth sides.

APT DATA COLLECTION AND RECONSTRUCTION

Figure 2 shows a schematic of the basic components of the atom probe used in this study. Field evaporation of atoms from the APT tip is achieved by subjecting the tip to a high direct-current voltage (typically beginning at approximately 0.5 kV), which produces a high field at the tip, just below the threshold necessary for field evaporation. Either an additional pulsed voltage or a pulsed laser (10 to 1000 kHz) is used to increase the field above the threshold necessary for field evaporation with each pulse, typically producing a field at the tip of up to several Vnm^{-1}.[13] Field-evaporated atoms are collected by a position-sensitive detector used to determine their original position on the tip, and time-of-flight information taken from the pulsed nature of the evaporation is used to determine the composition of each collected species (elemental and molecular). The number of collected atoms depends on the size of the area of interest and can range from a few tens of thousands to hundreds of millions of atoms, with detector efficiency ranging from 30% up to 80%, depending on the specific atom probe used and the material being evaporated. A spectrum of total counts as a function of mass-to-charge-state ratio provides information about the total number, isotopes, and ionization state of each evaporated species.

To reconstruct the captured volume in 3-D, the collected data are fed into an algorithm, which, in essence, pieces Humpty Dumpty back together again. A magnification transformation (for *x* and *y*) and a depth transformation (for *z*) are used in conjunction with an assumed hemispherical cap-on-a-cone tip shape with some defined shank angle.[14,15] A few parameters can be fine-tuned to

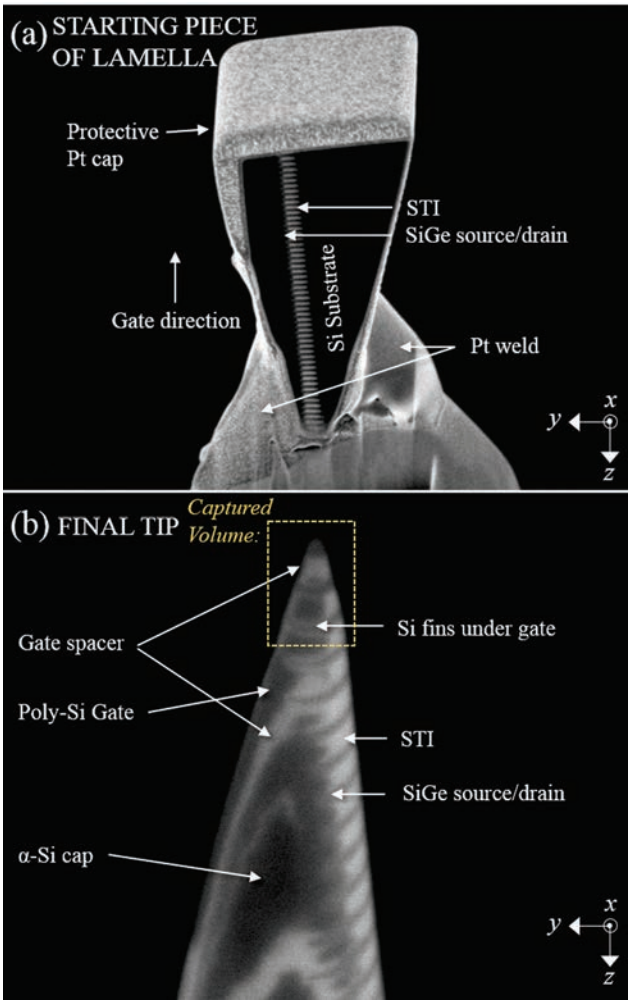

Fig. 1 **Scanning electron microscope images of (a) the starting piece of the lamella prior to APT tip shaping and (b) the final tip. Scale bars not shown for proprietary reasons**

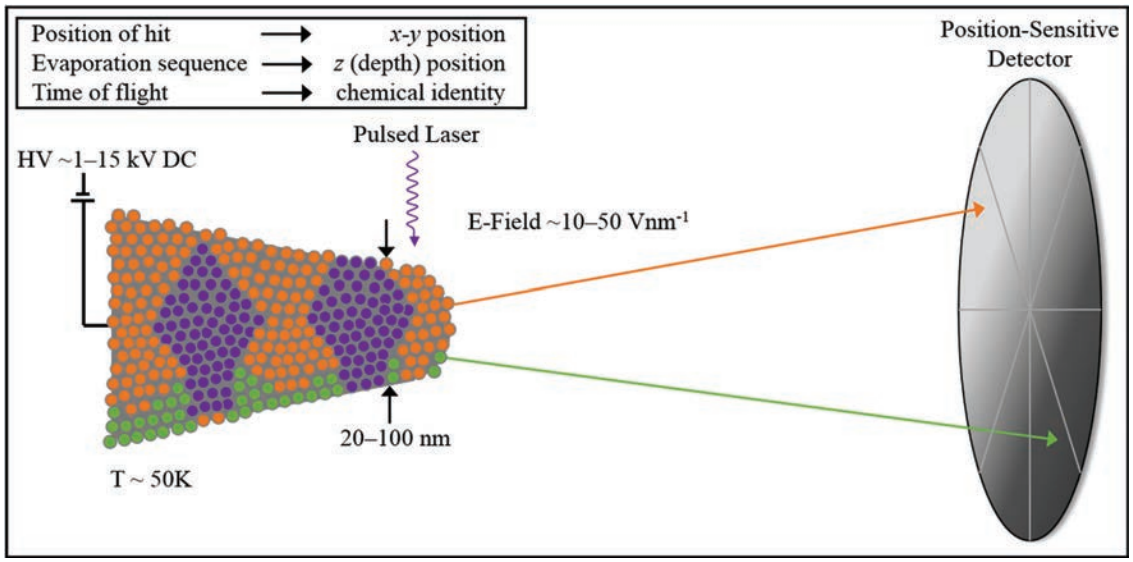

Fig. 2 **Schematic of the basic components of the atom probe as used in the study presented**

increase reconstruction accuracy (e.g., inputting a measured shank angle from high-resolution scanning electron microscope, or SEM, images; measurements of tip diameter at specific features). Once an accurate reconstruction is achieved, the sample is ready for 3-D analysis.

CASE STUDY: EPITAXIAL SiGe PROFILE AND DOPANT DISTRIBUTION FOR SOURCE/DRAIN FinFET DEVICE

The complex 3-D structure of state-of-the-art FinFETs, as shown in the schematic in Fig. 3, presents challenges for a number of characterization techniques. This study examines the use of 3-D APT to reveal structural and compositional characteristics of the SiGe source/drain region of the FinFET as well as light dopant profiles throughout the SiGe. The structure examined in this study consists of a specially designed array of fins and polysilicon ("dummy") gates, each with known pitch and length on the order of microns. Sample preparation was done following the cross-section preparation method demonstrated in Ref 1, which involves rotating the lamella 90° after liftout, such that the gates run parallel to the *z*-axis of the APT tip, with rows of fins running perpendicular to the tip in the *x*-direction, as shown in Fig. 1.

Field evaporation of the tip was done in a Cameca FlexTAP 3-D atom probe at 50 K under ultrahigh vacuum conditions (~3 · 10^{-11} torr) using an ultraviolet laser with starting energy of 35 nJ (spot size ~20 μm), which was slowly decreased throughout field evaporation as the voltage increased to maintain a Si++:Si+ ratio of approximately 10:1. The atom probe was operated at the maximum field of view of 30° to increase the captured cross section of the tip. The volume indicated in Fig. 1(b) was evaporated and collected. The collected atoms were reconstructed using the Integrated Visualization and Analysis Software package, which reconstructs the original tip with the capability of performing 3-D analysis not only of the tip surface visible in the SEM but of buried features as well.

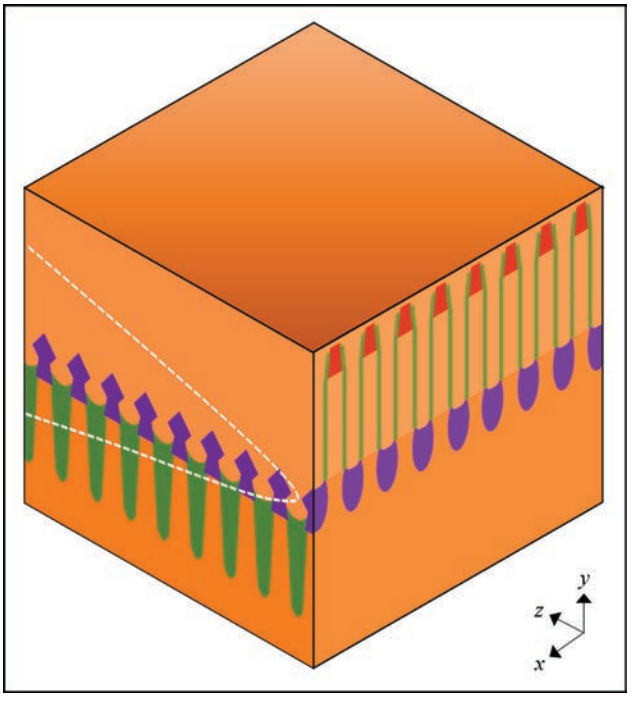

Fig. 3 **Schematic of the device structure analyzed by APT in this study. The dashed white line shows the position of the atom probe tip.**

A FIRST LOOK AT THE RECONSTRUCTED TIP

In the reconstructed volume, each collected element, molecule, and/or isotope (including various ionization states) can be shown in a different color and displayed or hidden from view as desired, to more clearly analyze different features. Furthermore, "cuts" can be made into the reconstruction at any location and orientation to reveal buried features, concentrations of various species can be

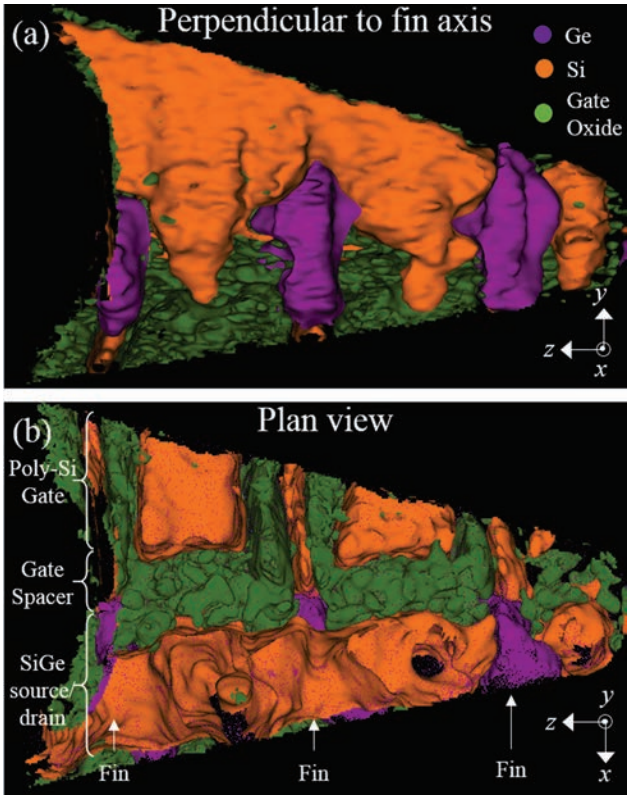

Fig. 4 **A 3-D APT reconstruction of the tip shown from (a) perpendicular to the fins perspective and (b) plan view (top-down perspective). Silicon, germanium, and the gate oxide are highlighted by isoconcentration surfaces of different colors as indicated in (a). Scale bars not shown for proprietary reasons**

measured from isolated regions and plotted or mapped in two dimensions, and 3-D isoconcentration surfaces can be highlighted. Examples of each of these forms of analysis will be used to examine these FinFET structures.

Atom probe tomography provides a unique capability to examine a structure from multiple perspectives without the need to prepare an additional sample or perform a secondary analysis. Figure 4 shows two different perspectives of the reconstructed tip: perpendicular to the fin axis (Fig. 4a) and top-down or plan view (Fig. 4b). Each image is a slice into the reconstruction, revealing buried features to more clearly show the desired structures. Three-dimensional isoconcentration surfaces of silicon, germanium, and the gate oxide are highlighted. These isoconcentration surfaces highlight a 3-D surface or "shell" of a given concentration, where everything contained within the bounds of that "shell" has a concentration equal to or greater than the highlighted surface. The isoconcentration surfaces for silicon and germanium show the 3-D shape and texture of these layers/structures. The SiGe source/drain regions are clearly seen in Fig. 4(a) highlighted by a germanium isoconcentration surface. In Fig. 4(b), the transition of the fin from SiGe to silicon can be observed from above as the fin passes under the gate spacer and subsequently under the polysilicon gate.

THE POWER OF 3-D ANALYSIS

The true power of 3-D APT is demonstrated by combining structural and chemical analysis of the buried fins. Figure 5(a) shows a 3-D view of the center source/drain SiGe shown in Fig. 4(a) and includes two-dimensional (2-D) germanium concentration maps taken at slices through the SiGe parallel to each axis. These maps provide detailed information about the 3-D germanium distribution within the SiGe as well as the complex nature of the SiGe shape. From Fig. 4(a) and 5(d), the top half of the SiGe appears diamond shaped. In Fig. 5(a), the 3-D SiGe shape can be seen more clearly, revealing faceting along the *x*-axis as well as *z*, which creates a conical protrusion in the *z*-direction. This faceting is also observed from the

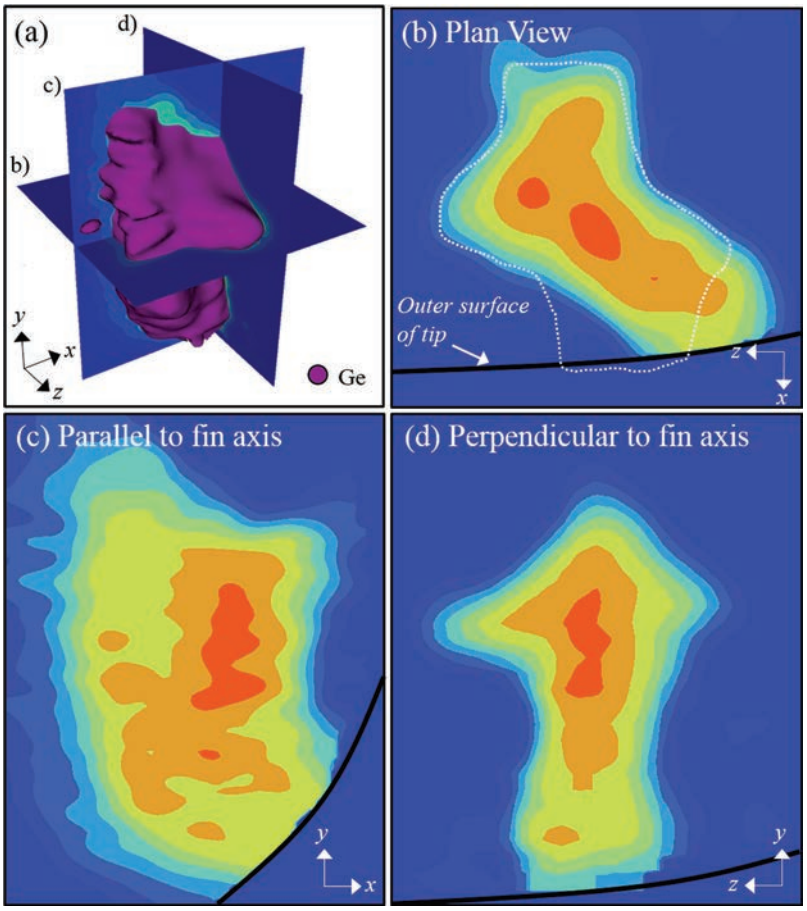

Fig. 5 **(a) A 3-D reconstruction of the SiGe source/drain region only, with a germanium isoconcentration highlighted to show the shape of the SiGe. (b) to (d) 2-D germanium concentration maps plotted from slices through the SiGe region at locations indicated in (a). Concentration and length scales not shown for proprietary reasons. The black solid line in (b) to (d) indicates the location of the outer surface of the APT tip. The dashed white line in (b) highlights the shape of the SiGe region from a plan-view perspective.**

plan view perspective (Fig. 5b) of the SiGe. Figure 6 shows a plot of the germanium and boron concentrations across the transition from the silicon fin to the SiGe source/drain region. The dashed white line in Fig. 5(b) highlights the faceted profile in the *x*-*z* plane. A distortion in the APT reconstruction causes the SiGe profile in the bottom right of Fig. 5(b) to skew toward the top of the tip (negative *z*-direction). Scanning transmission electron microscopy (STEM) images in Fig. 7(a), which were taken on another APT tip from the same sample, confirm this "plus" sign, faceted shape. The origin of this distortion to the SiGe is an undulating shape along the outer surface of the tip from one fin to the next along the *z*-axis. This wavy pattern, highlighted in Fig. 7(b), was formed as a result of differing FIB milling rates of the SiGe and neighboring oxide during tip shaping. A combination of more complex field evaporation due to the wavy shape and the assumption of a smooth outer surface by the reconstruction algorithm leads to some distortion along this surface. Minimizing distortions such as this and accurately understanding their source are just some of the many challenges facing the development of APT for semiconductor devices.

CHALLENGES IN APT

As APT matures into a staple characterization technique in a variety of fields, more and more challenges are continually met. Atom probe tomography in all fields of study will always face the challenge of improving our understanding of the field-evaporation process for various materials, particularly at interfaces, as well as reconstruction accuracy. This is particularly the case for samples containing layers, thin films, or isolated regions with very differing evaporation fields from the bulk of the sample. Much work has been done in both experimentation and simulation to understand the field-evaporation process in these situations and how to improve the reconstruction.[16-19] Semiconductor devices perhaps embody this challenge more than most other fields because, by nature, they contain a complex arrangement of metals, semiconductors, and insulators in close proximity. Even oxides as thin as a couple nanometers can create artifacts in neighboring semiconductor materials.[1] For semiconductor devices, the primary challenges facing APT can be grouped into three categories:

- Sample preparation
- Field evaporation through dissimilar material interfaces
- Elimination and proper interpretation of reconstruction artifacts

Isolating small or specific features on the nanoscale in the FIB is never easy. This is certainly true for semiconductor devices. This is further complicated by the fact that APT sample preparation requires isolating features in a conical tip rather than a planar lamella, as is the case for TEM. Differences in milling rates between different materials within semiconductor devices (e.g., SiGe compared to gate oxide) make it difficult to achieve the ideal tip shape necessary to satisfy the assumptions made by the reconstruction algorithm. Tip shaping is often as much of an art as a developed skill, and creativity in approaching different structures in unique ways can often reap benefits through thorough planning and meticulous preparation.

Field evaporation through interfaces of dissimilar materials requires a proper understanding of the materials involved and their order/orientation in order to optimize the APT operating conditions while passing through the

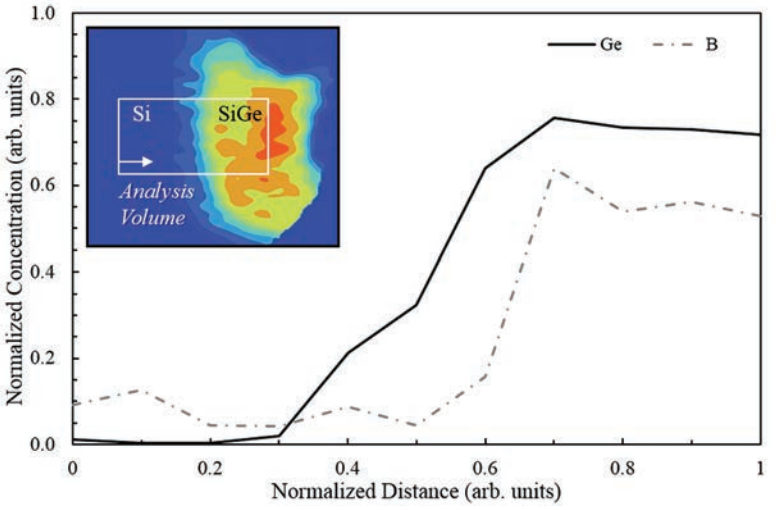

Fig. 6 **Germanium and boron profiles plotted from measurements across the silicon-to-SiGe transition of the fin, as indicated in the inset**

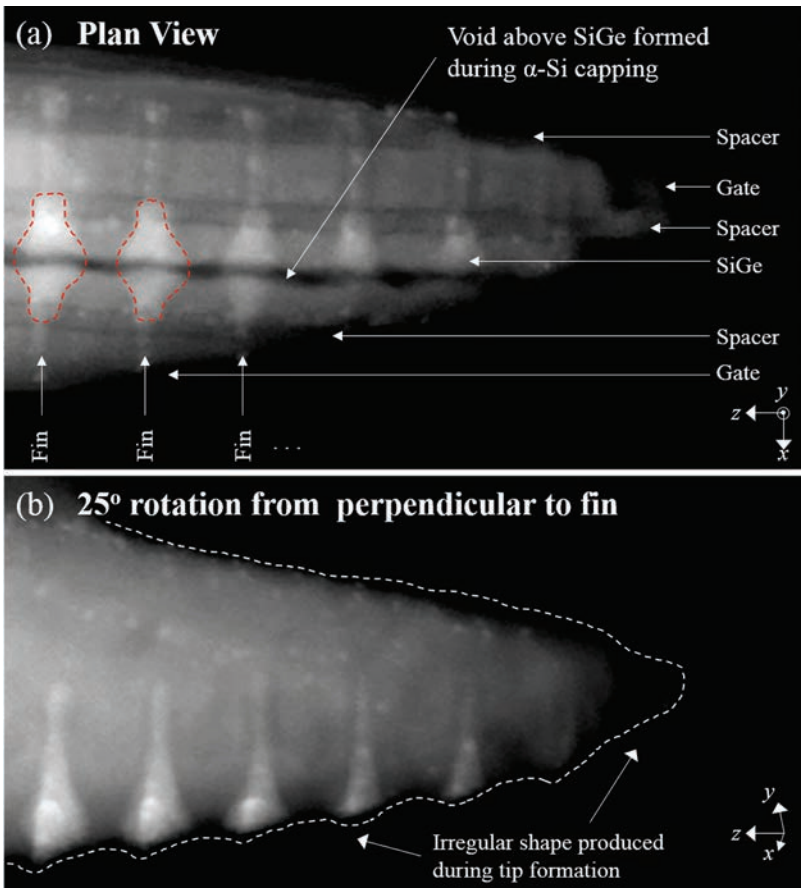

Fig. 7 **STEM images of a different APT tip shaped from the same sample. (a) Plan-view perspective of the tip with various features labeled. (b) Rotated view of the SiGe, highlighting the wavy shape of the outer surface of the tip. Scale bars not shown for proprietary reasons**

interface. Often, APT laser power, evaporation rate, or other parameters are altered to help with field evaporation through delicate or problematic interfaces to avoid premature tip rupture. However, it is important to understand the effects of altering such parameters on the integrity of the collected data. For example, increasing the laser power to assist field evaporation of a thin oxide layer may force the overall evaporation field in the surrounding silicon to stray from optimal. Likewise, decreasing the evaporation rate when moving through a region of insulating materials (e.g., gate oxide or spacer) to keep the tip from fracturing may significantly increase noise levels, making low dopant profiles in nearby SiGe source/drain regions more difficult to measure. These various trade-offs must be considered, and remaining artifacts, noise, and so on must be understood and properly interpreted if they cannot yet be eliminated.

CONCLUSION

Atom probe tomography has a unique capability to analyze even the most complex structures. Its combination of structural and chemical information for buried nanostructures makes it a one-of-a-kind resource in a number of fields and particularly for semiconductor devices. Atom probe tomography helps provide a clearer understanding of the shape and elemental composition of complex device structures and light dopant profile throughout these structures. Although many challenges still remain for sample preparation, improved understanding of APT data collection, and, most significantly, elimination of artifacts from the reconstructed 3-D data, APT remains a powerful tool for failure analysis and research and development of the next generation of advanced semiconductor devices.

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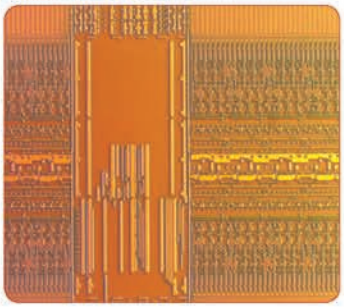
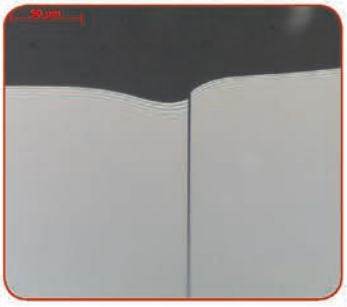
Capabilities include parallel polishing, angle polishing, site-specific polishing or any combination thereof. It provides reproducible results by eliminating inconsistencies between users, regardless of their skill.

Unequalled Sample P

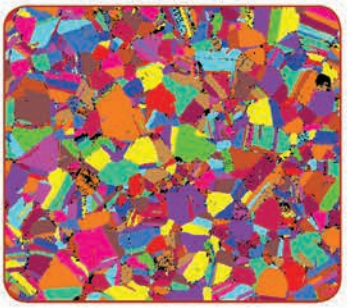


IC Delayering



TEM Preparation

Cross-Sectioning



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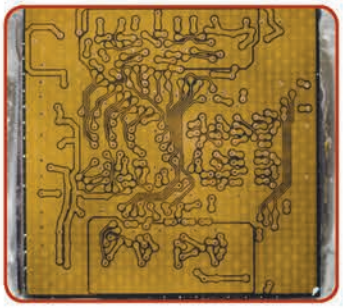
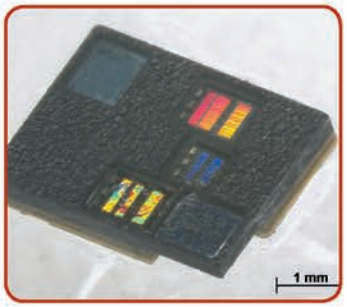
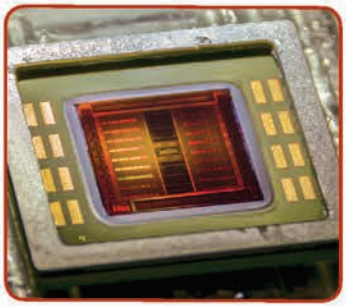
reparation Results



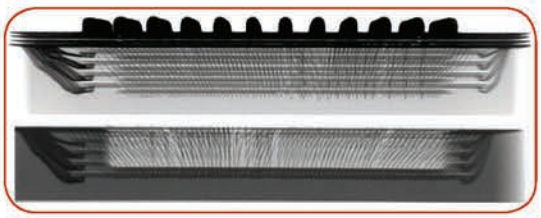
Uniform Substrate Delayering



Open areas as small as 100 x 100 µm



Visible & IR SIL Applications



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ADVANTAGES AND CHALLENGES OF 3-D ATOM PROBE TOMOGRAPHY *(continued from page 27)*

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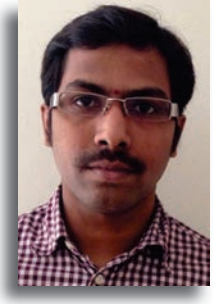

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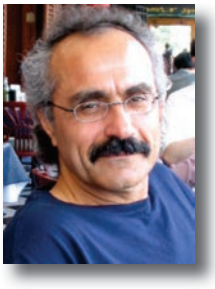

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CHARACTERIZING ORGANIC NANOCONTAMINATION IN SEMICONDUCTORS BY RESONANCE-ENHANCED NANOSCALE IR SPECTROSCOPY (AFM-IR)

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INTRODUCTION

For the last few decades, continuous development in semiconductor process technology has led to the fabrication of devices with nanometer-scale features.[1] Growth in the nanotechnology techniques used in producing micro-/nano-electromechanical components results in a growing interest for nanoscale surface analysis techniques that can complement or may replace the currently available tools. Resonance-enhanced AFM-IR is an emerging technique with the potential to overcome some limitations of the existing tools used in semiconductor fabs and failure analysis labs.

Organic contaminants are one of the major sources of surface contamination in the process development steps. Typical organic contaminants in the semiconductor fabrication facility include residual photoresists, human skin flakes, hair, and fabric from clothes and/or personal protective equipment such as gloves, lab coats, masks, and so on. Characterizing nanoscale organic contamination poses a major challenge to the traditional failure analysis technique, as discussed below.

BACKGROUND

Scanning electron microscopy coupled with energy-dispersive x-ray spectroscopy, one of the industry standards in surface analysis with nanometer-scale spatial resolution, offers useful chemical insight into surface defects and contamination; however, it provides minimal information for organic components. Among other alternative analytical techniques, infrared (IR) spectromicroscopy provides superior results in identifying organic materials but lacks spatial resolution. The traditional mid-IR spectromicroscopic defect analysis methods offer diffraction-limited detection resolution only up to 3 to 10 µm or larger.[2] Raman spectroscopy, on the other hand, provides similar chemical insight with submicrometer spatial resolution due to the short excitation wavelengths.[3] Nevertheless, the application of traditional Raman spectromicroscopy in nanoscale defect analysis is still limited due to experimental factors such as excitation wavelength, depth of penetration, and the transparency of microelectronic circuits.

"WHEN THE TRADITIONAL AFM IS COMBINED WITH IR SPECTROSCOPY, THE RESULTING AFM-IR TECHNIQUE PROVIDES HIGH-RESOLUTION TOPOGRAPHIC MAPS WITH THE ADDITION OF NANOSCALE CHEMICAL IMAGING AND SPECTROSCOPY."

Atomic force microscopy (AFM), a well-known scanning probe imaging technique, yields high-spatial-resolution topographic maps of a sample surface. Many surface-imaging techniques based on AFM also provide image contrast from material characteristics such as surface mechanical, electrical, and magnetic properties. While these properties can be mapped with high spatial resolution and can provide critical insight into the surface defects, none of these methods provide robust chemical analysis, especially for unknown materials. However, when a traditional AFM is combined with IR spectroscopy, the resulting AFM-IR technique provides high-resolution topographic maps with the addition of nanoscale chemical imaging and spectroscopy.

Previously, King et al. reported the applications of AFM-IR technology in nanoscale chemical and mechanical

characterization of nanopatterned metal and low-k dielectrics.[4] Their results demonstrated the sensitivity of the technique to isolate chemical modifications by the interconnect fabrication process. This article demonstrates the chemical characterization of the nanoscale skin and polyester contaminants on a silicon wafer using resonance-enhanced AFM-IR spectroscopy.

RESONANCE-ENHANCED AFM-IR

In the AFM-IR technique, the IR spectral intensity is recorded in terms of mechanical force experienced by an AFM cantilever due to photothermal expansion of the absorbing molecules. A detailed account of the underlying theory and correlation between optical, mechanical, and thermal properties in AFM-IR are described elsewhere[5] and are beyond the scope of this report. It has been demonstrated that the AFM-IR technique detects only the heating and thermal expansion perturbations directly underneath the AFM tip; spatial resolution is significantly below the optical diffraction limit of the IR wavelength.[5,6]

Resonance-enhanced AFM-IR was introduced to enhance the sensitivity of the traditional AFM-IR for thinner samples by using a high and tunable repetition-rate IR source—quantum cascade lasers (QCLs).[7,8] This pulse-rate tunability allows the user to synchronize the laser pulses with a resonance frequency of the AFM cantilever. This synchronized pulsing gives rise to a high IR sensitivity mode due to resonance enhancement of the cantilever oscillation, typically providing a gain in sensitivity by a factor of 30 to 50 (Fig. 1).

The QCL source for the resonance-enhanced mode has recently been upgraded to allow faster acquisition of spectra over the full tuning range, allowing a reduction in spectral acquisition time of a factor of 10 to 100. Earlier, the data acquisition took place by stepping to each wavenumber and measuring the oscillation amplitude of the AFM cantilever to collect the AFM-IR spectrum. In the new implementation, the QCL is swept over its range, and the cantilever oscillation amplitude is measured simultaneously with the wavelength change. This enables significant advancements in the data-acquisition protocol and vastly impacts the measurement throughput by allowing faster sample analysis or more data averaging. In addition, the faster spectra can diminish the effects of thermal drift, which improves the robustness and reproducibility of the site-specific data, especially for dimensions <100 nm.

Combined ultrahigh sensitivity and fast spectral acquisition in the resonance-enhanced mode has a tremendous impact by allowing widespread use of nanoscale IR spectroscopy for spatially resolved chemical characterization of nanoscale materials down to a thickness of 1 nm.

APPLICATIONS OF RESONANCE-ENHANCED AFM-IR IN FAILURE ANALYSIS

Contaminated silicon wafers were prepared in the lab, using known materials typical of those found in the semiconductor fab environment, and analyzed. For each sample, high-resolution tapping-mode AFM images were acquired to locate the contaminants, followed by the AFM-IR measurements.

The tapping-mode AFM height image (Fig. 2a) illustrates the thickness variation (20 to 100 nm) of the contaminant residue (human skin tissue) on one of the test silicon wafers. After locating the desired site from the AFM image, the QCL pulse rate is tuned to one of the cantilever oscillation modes (~170 kHz, 2nd mode), and the laser is swept in the fast-acquisition mode to acquire resonance-enhanced AFM-IR spectra (Fig. 2b). The measurements were performed at sites with varied thicknesses (20 to 100 nm), as indicated in Fig. 2. Observed IR intensity

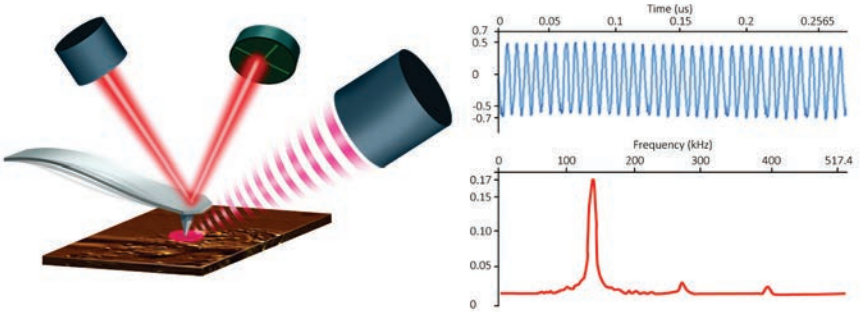

Fig. 1 **(a) Resonance-enhanced AFM-IR operation: rapid thermal expansion experienced by AFM cantilever subsequent to IR absorption. (b) Cantilever oscillations due to IR absorption and (c) fast Fourier transform of the oscillation signal. Laser pulse rate is tuned to cantilever oscillation mode for resonance enhancement.**

changes with the sample thickness, as expected; however, the overall signal-to-noise ratio is sufficient to accurately identify the material over the whole thickness range. This reflects the excellent sensitivity of the resonance-enhanced mode for characterizing thin samples.

Resonance-enhanced AFM-IR spectra on a second sample are shown in Fig. 3 after locating the surface contamination by regular AFM. Observed spectra are compared against the Fourier transform infrared (FTIR) database (KnowItAll, Bio-Rad Inc.) and positively identified as polyethylene terephthalate (PET), a polymer typically used in polyester fabric. Figure 3 (also Fig. 2) illustrates that fast spectral acquisition does not affect spectral resolution and sensitivity.

CONCLUSIONS AND FUTURE

Resonance-enhanced AFM-IR has been demonstrated as a powerful characterization tool for identifying organic contamination in semiconductor fabrication. It offers superior sensitivity for organic materials with high spatial resolution compared to traditional analytical tools used in failure analysis. In addition, true model-free correlation with traditional FTIR spectra augments the reliability of nanoscale defect characterization.

New-generation AFM-IR technology, such as tapping AFM-IR and hyperspectral measurements, is currently under progress. These developments facilitate enhanced

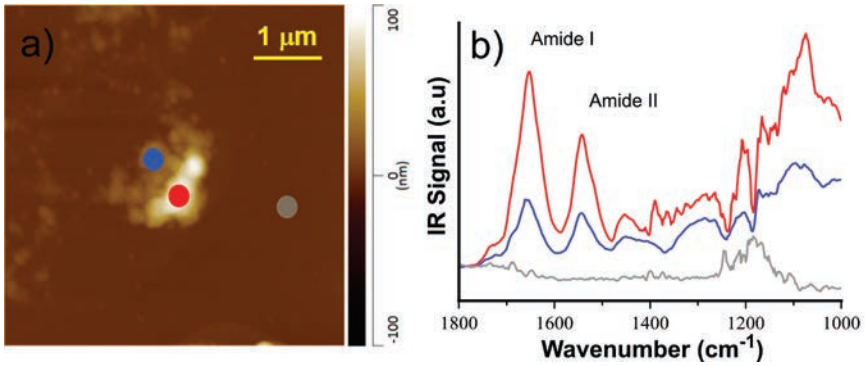

Fig. 2 **(a) Tapping-mode AFM image (height) of human skin residue on a silicon wafer. (b) Corresponding AFM-IR spectra. Amide I and II bands are indicated.**

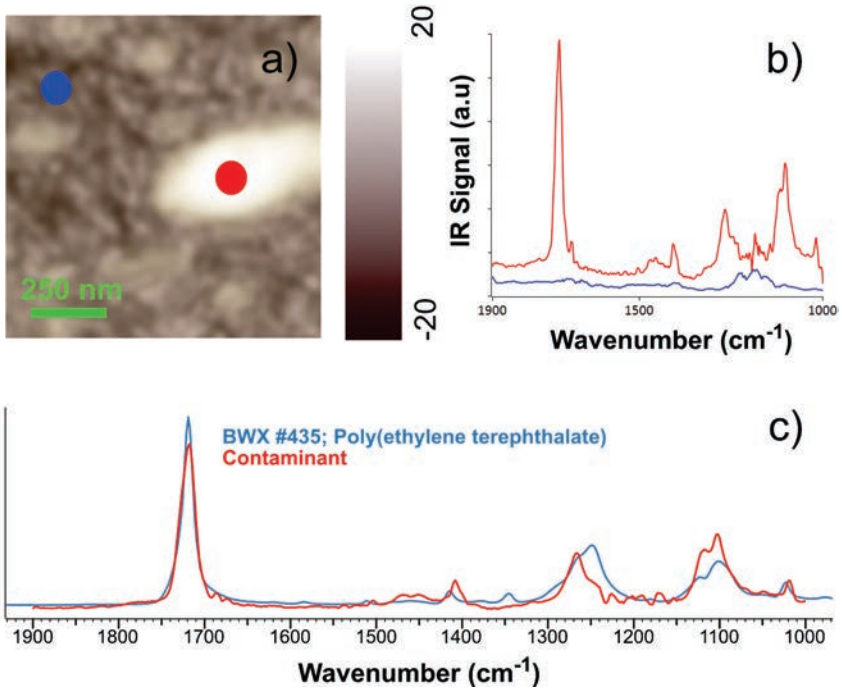

Fig. 3 **(a) Tapping-mode height image of another wafer with organic residue. (b) AFM-IR spectra on (red) and off (blue) the contaminant. (c) Comparison of the measured AFM-IR spectra (red) of the organic residue against the FTIR spectra (blue)**

sensitivity, spatial resolution, and robust statistical analysis to broaden the range of applications in failure analysis addressed by nanoscale IR spectroscopy.

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NOTEWORTHY NEWS

ESREF 2017

The 28th European Symposium on Reliability of Electron Devices (ESREF '17) will take place **September 25 to 28, 2017**, in Bordeaux, France. The international symposium continues to focus on recent developments and future directions in quality, robustness, and reliability research of materials, devices, components, and circuits for nano-, micro-, power-, optoelectronics, and MEMS sensors. It provides the leading European forum for developing all aspects of reliability management as well as innovative microstructure and techniques for present and future electronics. At ESREF 2017, the aeronautics, space, and embedded systems industries will provide specific topics, such as radiation hardening, very long-term reliability, high-/low-temperature challenges, obsolescence and counterfeit issues, wide band-gap power devices for electric aircraft, and other embedded system applications.

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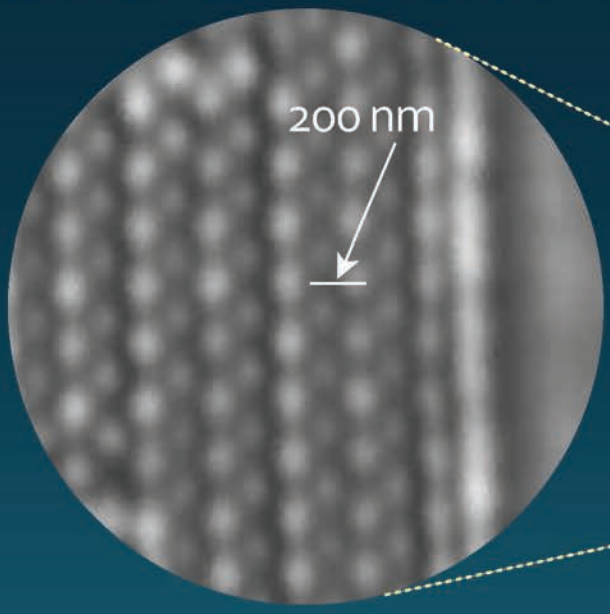
All images taken

14 nm device with spacing
between nodes of about 200 nm



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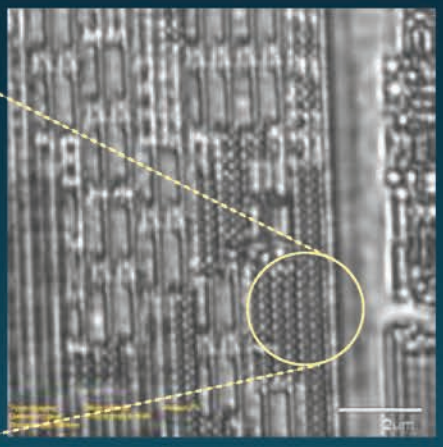
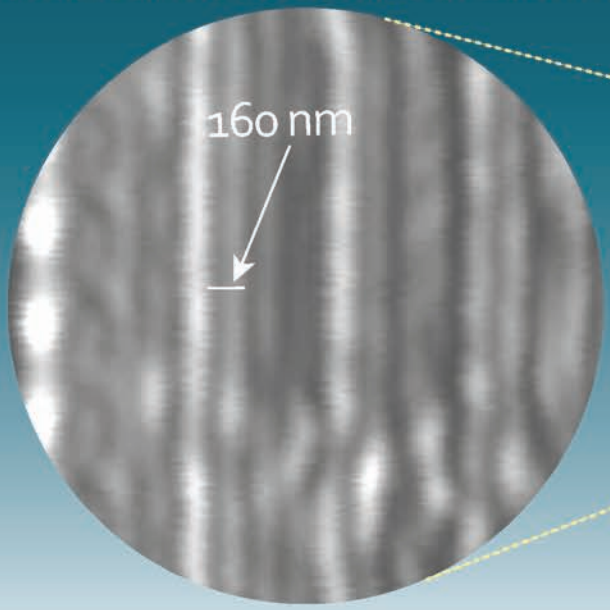
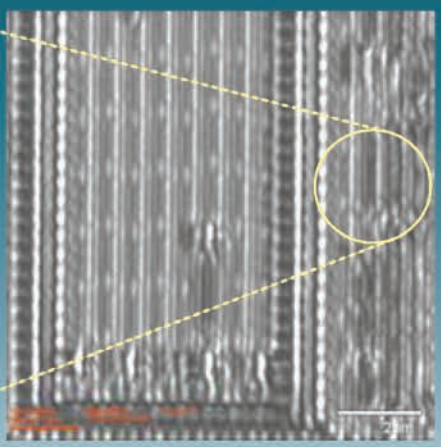
Polaris GP RX 480



14 nm process by Samsung with spacing
between vertical lines of 160 nm



Nvidia
GP107



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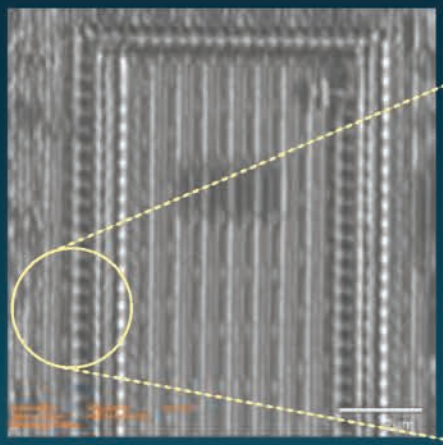
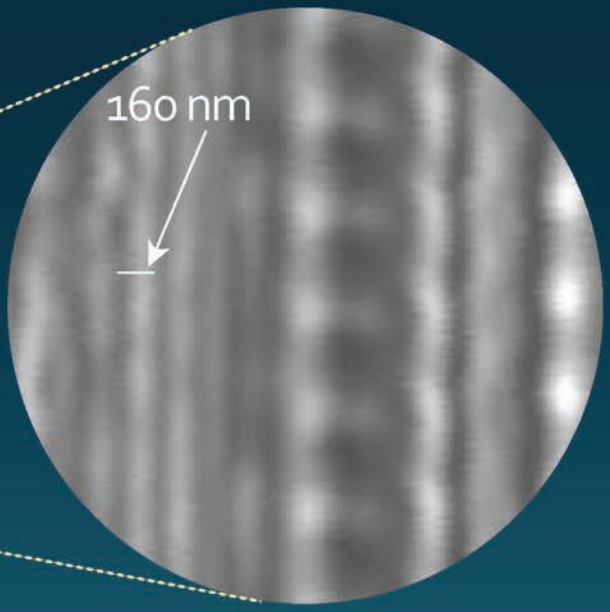
14 nm process by Samsung with spacing between vertical lines of 160 nm

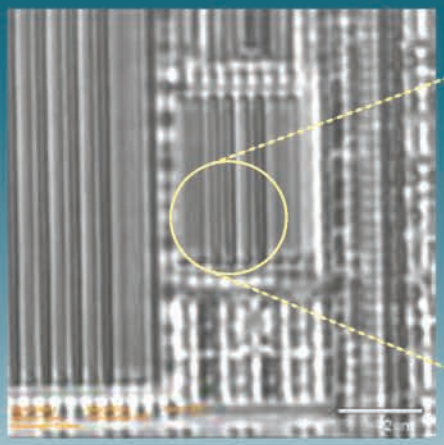
Nvidia
GP107

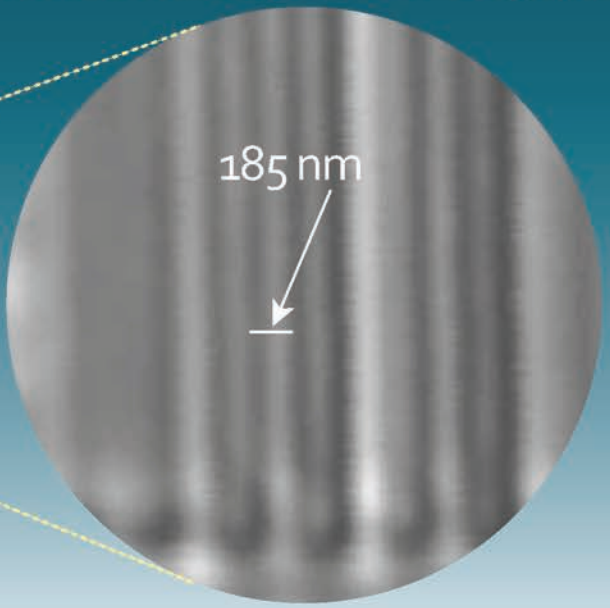




14 nm device with spacing between vertical lines ~185 nm

Intel 14 nm Skylake
Xeon E3 1220 v5





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EDFAS 2017 PHOTO CONTEST

OPEN TO ALL MEMBERS OF THE FAILURE ANALYSIS COMMUNITY!

SHARE YOUR BEST IMAGES WITH THE FAILURE ANALYSIS COMMUNITY AND BE RECOGNIZED FOR CREATING THEM!

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Where: Selected entries will be displayed and prizes awarded November 5-9, 2017, at the 43rd International Symposium for Testing and Failure Analysis (ISTFA) Conference and Exposition in Pasadena, California.

Categories: No more than one image per person allowed in each category

I. *Color Images Only* (*Optical Microscopy*)

II. *Black & White Images Only* (*Optical Microscopy/SEM/TEM/X-Ray/UV Micrographs/Other*)

III. *False Color Images Only* (*SPM/SAM/Photon Emission/Other*)

Images will be judged on failure analysis relevance (35%), aesthetics (35%), and novelty of the technique or mechanism (30%).

Deadline: Entries must be submitted by September 1, 2017.

Entries: Submit by e-mail to **photocontest@edfas.org** (subject line: EDFAS Photo Contest).

Format: Submissions should be made through e-mail only, with one picture attached. Each submission must be in a standard format (PNG, JPEG, TIFF, BMP, etc.). Please provide your highest-resolution image. The preferred submission is a .jpg or .tif, five inches wide at 300 dpi resolution.

Along with the picture, the e-mail should include the name of the submitter, category of submission, mailing address, phone, fax, e-mail address, and a description of the micrograph (not exceeding 50 words). The picture should not have any contact information embedded.

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Prizes: **1st place** in each category receives a wall plaque and one-year complimentary EDFAS membership.

2nd and 3rd places in each category receive award certificates and one-year complimentary EDFAS memberships.

The top 10 entries in each category will be displayed at ISTFA 2017 in Pasadena, California.

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ARE YOU THE NEXT SCORSESE OF FAILURE ANALYSIS? WE HOPE SO!

Submit your 3 minute (or less) video about an exciting result or a scintillating artifact—anything goes as long as it relates to failure analysis! Your FA community will judge them and recognize winners at this year's ISTFA. Show off your filmmaking skills and FA prowess. **Upload your video today!**

Format: MPEG or AVI format with a maximum size of 50 MB. The video should be 3 minutes or less. Audio and subtitles are allowed. A short description should also be submitted along with all of your complete contact information.

Categories: **Failure Analysts:** Anyone working in the failure analysis field

Students: Students currently studying in fields related to failure analysis (physics/electrical engineering/chemistry/materials science, etc.)

Exhibitors

Deadline: October 1, 2017

Entries: Go to https://asm.confex.com/asm/istfa17/cfp.cgi

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Prizes: **1st place** receives a $50 gift card, a complimentary registration to a future ISTFA conference, and a 1st place winner plaque.

2nd place receives a $25 gift card and award certificate.

3rd place receives an award certificate.

(Note: 2nd place will be awarded if total submissions are more than 10; 3rd place will be awarded if total submissions are more than 15.)

The top 10 entries in each category will be displayed at ISTFA 2017 in Pasadena, California.

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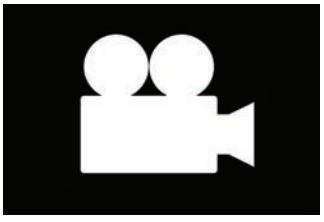

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UNIVERSITY HIGHLIGHT

"WHAT STARTS HERE CHANGES THE WORLD:" RESEARCH HIGHLIGHTS FROM THE UNIVERSITY OF TEXAS AT AUSTIN, MICROELECTRONICS RESEARCH CENTER (MRC)

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The University of Texas at Austin

In the November 2016 issue of *EDFA*, research from the University of Texas at Austin's Department of Physics was emphasized. In this issue, research from the university's Microelectronics Research Center (MRC) is highlighted. The MRC was originally founded by Professor (Emeritus) Ben Streetman in 1984. The MRC mission is "to perform education, research, and development in materials and electronic devices." The center is funded by the National Science Foundation.[1] Research areas focus on new devices and integrated circuits, physics of small-scale devices, device processing, advanced crystal growth, and new approaches to device packaging and interconnects. The MRC emphasizes an interdisciplinary approach and industry collaboration.

Professor Jack Lee[2] is one of the most well-known members of the MRC. He has taught many semiconductor short courses for industry, including some at Advanced Micro Devices while I was there. As a student of Chenming Hu, he won the Best Paper at the IEEE International Reliability Physics Symposium for his studies on SiO_2 gate dielectric reliability.[3] Since then, Dr. Lee has won many awards. His current research at the MRC focuses on ferroelectrics and high-k gate dielectric materials.[4-7]

Professor Sanjay Banerjee, current director of the MRC, runs the Nanoelectronics and Novel Devices Lab. He, too, is well known in the industry and has won numerous awards.[8] His book, *Solid State Electronic Devices*, written with Ben Streetman, is a very popular textbook for device physics courses. Dr. Banerjee's current research interests are MOS and nanostructure device modeling, Si-Ge-C heterostructures, photovoltaics, and ultrashallow junction technology.

Professor Edward Yu administers the Nanoscale Characterization and Devices Group.[9] His group conducts research on photovoltaics plus other technologies for generating and storing energy, nanoscale imaging and characterization using scanning probe technologies, and semiconductor materials and solid-state nanostructure devices.

Professor Paul Ho directs the Interconnect and Packaging Research Group.[10] His research covers 3-D interconnects, chip packaging, electromigration, nanodevices, low-k materials, stress migration, and time-dependent dielectric breakdown. Some of his articles on the study of stresses in through-silicon vias and electromigration have been highlighted in *EDFA* magazine's peer-reviewed literature column.[11-13]

Professor Li Shi's research group (Nanomaterials and Thermo-Fluids Laboratory) has won numerous awards for its research, which covers thermal management of nanoelectronic devices, solar cells, and nanoscale transport phenomena.[14,15] His research group uses scanning probe microscopy techniques to characterize thermal transport in nanostructure devices, which has led to a better understanding of transport processes in nanomaterials.[16-19] Some of his articles were featured in the February issue's peer-reviewed literature column.

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INVENTOR'S CORNER

THE PASSION OF INVENTING

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After graduating from Purdue University, I started out at Delco Electronics in 1986 and really enjoyed the work plus the lasting friendships that formed. I helped solve a pinhole oxide problem that had plagued the fab for years by using a hole in aluminum foil on an old Bausch & Lomb illuminator, forming a small spot of light. Scanning the light manually across the read-only memory row line, I identified the locus of the failure by monitoring the change in leakage. Corrective action ensued based on scanning electron microscopy (SEM) images of the pinhole. Approximately one year into the job, the economy went sour for automotive electronics. I got a job interview with AMI Semiconductor in Pocatello, Idaho, and went west.

The AMI fab had issues with oxide leakage, and this is when I first conceived passive voltage contrast, which is still widely used today. The gate oxide (GOX) test structures frequently failed at probe, and the root cause was identified as damaged GOX without an understanding of when this occurred in the process. Passive voltage contrast allows differentiation of conductors from insulators, using the electron beam at various tilt angles. It was determined that the GOX damage occurred before the source/drain implant. This meant the poly plasma etch process was to blame, and successful corrective action ensued. Passive voltage contrast became an in-line screen at AMI. The work was published at the EOS/ESD Symposium and ISTFA 1990.

PATENTS: US5892539, US5764409, US6112004

I left AMI and went to Fremont, Calif., to work for Waferscale Integration, Inc. (WSI). I managed the failure analysis lab and had minimal equipment to work with in the beginning: a wire-caged lab equipped with an SEM, analog oscilloscope, optical microscope, and an old probe station. Over the years, with the support of a great manager, I was able to build the lab, adding a confocal microscope, memory tester, probe station with laser cutter, and so on. We needed photon emission capability, so I looked at what was available. After seeing how poorly they were designed and how hard they were to use, I concluded that I could build my own. A frame-edit videocassette recorder and a Sony extended infrared charge-coupled device sensor ended up smoking the doors off the current "scientific-grade" and Gen III intensified systems at a fraction of the cost. I contracted with Alpha Innotech (a bio-tech company) to add the FA1000 photon emission and vibration couplers to allow portable test head interfaces to their product offering. This system sold very well for them.

PATENTS: US7872485, US7323888

After seven years at WSI, I resigned and have been pursuing my own ventures since 2000.

I realized a need in the industry for localizing fault locations. I conceived the idea of rastering a laser over the die while looping test functionally. Coordinating the laser position to the pass/fail status along with synchronized I_{dd} mapping could provide this fault isolation. Ultimately, this concept became the stimulus-induced fault test (SIFT) tool. I published this work in 2002 and had up to one year after publication to patent it. I filed the provisional patent in August 2003.

PATENTS: US8797052, US9411002

Building on the SIFT work, I then developed time-of-flight SIFT (TOFSIFT). Realizing that the industry was moving to stacked dice or situations with no direct access to the active layers, I began to experiment with pulsed heat from a CO_2 laser to measure the propagation time and therefore the distance to a known substrate diode. The target area must be able to withstand the laser power. This technique uses a continuous-wave thermal laser to heat the device under test locally at known coordinates and cycle the beam as a function of the propagation time it takes the thermal wave to reach the defect. By trilateration at different stimulus points, the defect can

be localized in 3-D space, which is useful for stacked dice analysis. Preliminary results were obtained by locally heating the substrate or the exposed copper paddle. This method overcomes the pitfalls of using thermal cameras to measure the phase of heat at the surface. The assumption is that enough power could be poured into a localized defect to reach the surface, but it quickly devolves into providing hundreds of milliwatts of required power with lengthy time constants and risks overstressing the defect. However, with TOFSIFT the device temperature is changed by external means, and the resulting time variant response is used to trilaterate temperature-sensitive localized functional or parametric failures. Both methods are affected by variations in thermal conductivity, especially air gaps, and generally assume a localized failure. In the event where it is not practical to do TOFSIFT, a thermal gradient can be forced from one end of a device or wafer to the other. The point where the gradient temperature matches the defect is the location in the *X*-plane of the defect. The same method is applied to the *Y*-plane to localize the defect. This is especially useful with temperature-sensitive failures on higher-power devices such as computer processing units. Temperature-forcing the opposing ends of a large metal block as a heatsink provides the required cooling with a controllable gradient to map sensitivities. In recent years, stacked dice can include as many as 15 dice, with each die on the order of 30 µm thick. This is quite conducive to forcing thermal gradients because the silicon substrate is minimally present. A commercial product has not yet been produced for TOFSIFT, but I am interested in a collaborative development of such a product.

PATENT: US6245586

We know that not all packages are created with failure analysis in mind. Ball grid array products or stacked dice products with wire bonding embedded in epoxy cannot be analyzed through the backside if the die is facing up. Pocket milling severs balls and traces in the package when trying to access the substrate. While it is possible to probe the exposed bonds, it is not realistic for more than a few connections. The solution is to polish away the package and backside polish the die, disregarding the electrical connections. Once the desired polish is achieved, the severed and polished wires become the new bond pads. The die can now be wire bonded to a new package or carrier for test.

PATENTS: US9465049, US9157935, US9034667

Sample preparation involving ultrathin silicon is of current interest. Being able to target to 1 µm of remaining silicon pushes the need for thinning tools capable of system temperature control and electrical endpoint detection during preparation. Modeling the top surface and hoping the part will not deform further is unrealistic. Polynomial curve models are used to define the final surface a priori. This work won the Best Paper award at ISTFA 2012 for the development of electrical endpoint techniques on silicon and at the package/board trace level for circuit surgery/access.

I've found that I love the inventing side much more than the administrative side of business. I enjoyed developing portable emission microscopy and vibration coupler applications as well as SIFT fault isolation methods, wire-to-wire bonding, and, more recently, integrated parametric and thermal capabilities into sample ultrathinning, to name a few of my 15 issued patents. However, starting a manufacturing business is quite different from consulting for other companies. Valuable advice given to me by a chief executive officer friend of mine was: Be in charge of your operation or walk away. I have taken this lesson to heart. I'll probably write a nail-biting book on this topic after I retire. Being an inventor means wanting to invent and avoid the politics. However, business relationships will always be part of the package. With all the consolidation of companies, the playing field is changing, but from the failure analysis perspective, there will always be problems to solve and, as such, the need for technological advancements. Be sure your management sees you as an indispensable resource to your company because of your problem-solving skills. Being successful in failure analysis requires you to be inventive with the tools on hand (and sometimes the political situation) to solve complex problems. The impossible answers usually come in the next few days. Always let the data lead you by using the process of elimination to distill out a solution, and enjoy the challenge.

The author may be contacted for questions at jbcolvin@pacbell.net. Publications and patents can be referenced at fainstruments.com in the "About Us" and "Library" links.

PRODUCT NEWS

PRESS RELEASE SUBMISSIONS:
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NATIONAL INSTRUMENTS UPGRADES ALL-IN-ONE VIRTUALBENCH

National Instruments (Austin, Texas) announced the VB-8054 instrument, a new higher-performance model of VirtualBench. VirtualBench plays a key role in reducing the cost and footprint of test and measurement systems by consolidating five of the most commonly used instruments into one device without compromising the performance of each instrument. Combined with a modern software experience and simple programming interface, VirtualBench creates new efficiencies for engineers interacting with benchtop test equipment or developing low-cost automated test systems.

National Instruments' VB-8054 and VirtualBench Windows software application

"Engineering workbenches and test systems are getting more and more crowded every day as technologies converge in the latest smart devices," said Luke Schreier, Director of Automated Test Product Marketing at National Instruments. "VirtualBench provides the ideal combination of capability at performance levels that can legitimately replace five or more instruments needed to characterize new product designs or validate assembled units on a production floor. With 500 MHz of scope bandwidth and a faster generator in the latest model, VirtualBench meets the needs of even more engineers wrestling with how to lower their cost of capital equipment."

Key new features of the VB-8054 include:

- Four-channel, 500 MHz mixed-signal oscilloscope with 2 GS/s sampling rate and protocol analysis (34 digital channels)
- Function generator with 40 MHz max sine output, 5 MHz square, ramp/triangle, direct current (dc) and arbitrary modes

The VirtualBench family has the following additional capabilities:

- True 5½ digital multimeter with 300 V input range, three-channel programmable dc power supply (up to 3 A) and eight general-purpose digital input/output lines
- Intuitive, unified software view of all five instruments, visualization on larger displays, and quick functionality to save data and screenshots
- Universal serial bus (USB), ethernet, and WiFi connectivity to Microsoft Windows software application and WiFi connectivity to Apple iPad software application
- Programming interfaces to automate measurements in LabVIEW and C environments

The VirtualBench application requires zero installation and can load automatically through Windows AutoPlay when connected through USB. VirtualBench also includes software capabilities such as digital phosphor density maps for displaying multiple acquisitions simultaneously, *XY* mode for plotting channels against one another, and hands-free smart capture for automatic data capture of repeated stable waveforms. To help better maintain the value of any VirtualBench investment, National Instruments provides free software and firmware updates as new features are released. These features, in addition to the consolidated interface, help engineers streamline their approach for benchtop characterization and validation. The small footprint and low price of VirtualBench compared with its equivalent set of boxes help enable lower cost of test on a manufacturing floor.

The VirtualBench hardware family consists of three models most easily designated by oscilloscope analog bandwidth: 100, 350, and 500 MHz. Through these models, the VirtualBench family serves a wide range of applications and price points in academic labs, hardware characterization/debug benches, and automated test systems.

For more information: e-mail: beth.williams@ni.com; tel: 512.683.6394; web: ni.com/white-paper/53568/en/.

ENGINEERS SHRINK MICROSCOPE TO DIME-SIZED DEVICE

Researchers at The University of Texas at Dallas (Richardson, Texas) have created an atomic force microscope (AFM) on a chip, dramatically shrinking the size—and, hopefully, the price tag—of a high-tech device commonly used to characterize material properties.

"A standard AFM is a large, bulky instrument, with multiple control loops, electronics, and amplifiers," said Dr. Reza Moheimani, professor of mechanical engineering at UT Dallas. "We have managed to miniaturize all of the electromechanical components onto a single small chip."

Moheimani and his colleagues describe their prototype device in the article "On-Chip Dynamic Mode Atomic Force Microscopy: A Silicon-on-Insulator MEMS Approach," published in the February 2017 issue of the *IEEE Journal of Microelectromechanical Systems*.

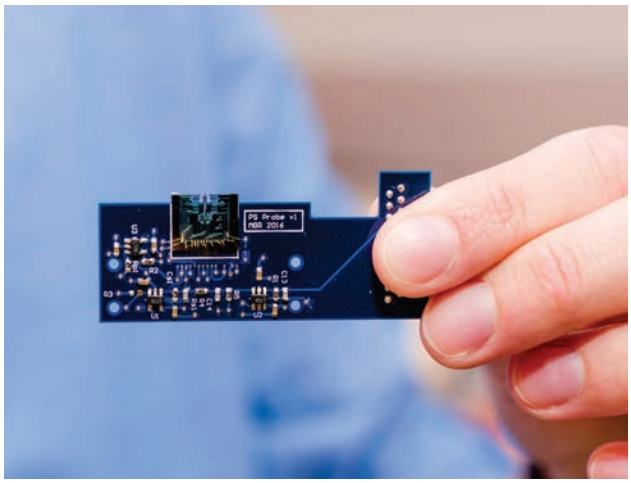
An AFM is a scientific tool that is used to create detailed three-dimensional images of the surfaces of materials, down to the nanometer scale—that's roughly on the scale of individual molecules.

The basic AFM design consists of a tiny cantilever, or arm, that has a sharp tip attached to one end. As the apparatus scans back and forth across the surface of a sample, or the sample moves under it, the interactive forces between the sample and the tip cause the cantilever to move up and down as the tip follows the contours of the surface. Those movements are then translated into an image.

"An AFM is a microscope that 'sees' a surface kind of the way a visually impaired person might, by touching. You can get a resolution that is well beyond what an optical microscope can achieve," said Moheimani, who holds the James Von Ehr Distinguished Chair in Science and Technology in the Erik Jonsson School of Engineering and Computer Science. "It can capture features that are very, very small."

The UT Dallas team created its prototype on-chip AFM using a microelectromechanical systems (MEMS) approach.

"A classic example of MEMS technology is the accelerometers and gyroscopes found in smartphones," said Dr. Anthony Fowler, a research scientist in Moheimani's Laboratory for Dynamics and Control of Nanosystems and one of the article's co-authors. "These used to be big, expensive mechanical devices, but using MEMS technology, accelerometers have shrunk down onto a single chip, which can be manufactured for just a few dollars apiece."



MEMS-based AFM attached to a small printed circuit board

The MEMS-based AFM is approximately 1 cm^2 in size, or a little smaller than a dime. It is attached to a small printed circuit board, approximately half the size of a credit card, which contains circuitry, sensors, and other miniaturized components that control the movement and other aspects of the device.

Conventional AFMs operate in various modes. Some map out a sample's features by maintaining a constant force as the probe tip drags across the surface, while others do so by maintaining a constant distance between the two. "The problem with using a constant-height approach is that the tip is applying varying forces on a sample all the time, which can damage a sample that is very soft," Fowler said. "Or, if you are scanning a very hard surface, you could wear down the tip."

The MEMS-based AFM operates in tapping mode, which means the cantilever and tip oscillate up and down perpendicular to the sample, and the tip alternately contacts and then lifts off from the surface. As the probe moves back and forth across a sample material, a feedback loop maintains the height of that oscillation, ultimately creating an image.

"In tapping mode, as the oscillating cantilever moves across the surface topography, the amplitude of the oscillation wants to change as it interacts with the sample," said Dr. Mohammad Maroufi, a research associate in mechanical engineering and co-author of the paper. "This device creates an image by maintaining the amplitude of oscillation."

Because conventional AFMs require lasers and other large components to operate, their use can be limited. They are also expensive. "An educational version can cost about $30,000 or $40,000, and a laboratory-level AFM can run $500,000 or more," Moheimani said. "Our MEMS

approach to AFM design has the potential to significantly reduce the complexity and cost of the instrument. One of the attractive aspects about MEMS is that you can mass produce them, building hundreds or thousands of them in one shot, so the price of each chip would only be a few dollars. As a result, you might be able to offer the whole miniature AFM system for a few thousand dollars."

A reduced size and price tag also could expand the AFM's utility beyond current scientific applications. "For example, the semiconductor industry might benefit from these small devices, in particular, companies that manufacture the silicon wafers from which computer chips are made," Moheimani said. "With our technology, you might have an array of AFMs to characterize the wafer's surface to find microfaults before the product is shipped out." The lab prototype is a first-generation device, Moheimani said, and the group is already working on ways to improve and streamline the fabrication of the device.

"This is one of those technologies where, as they say, 'If you build it, they will come.' We anticipate finding many applications as the technology matures," Moheimani said.

Moheimani's research has been funded by UT Dallas startup funds, the Von Ehr Distinguished Chair, and the Defense Advanced Research Projects Agency.

TERAHERTZ CHIPS OFFER NEW WAY OF SEEING THROUGH MATTER

Electromagnetic pulses lasting one millionth of a millionth of a second may hold the key to advances in medical imaging, communications, and drug development. However, the pulses, called terahertz waves, have long required elaborate and expensive equipment to use.

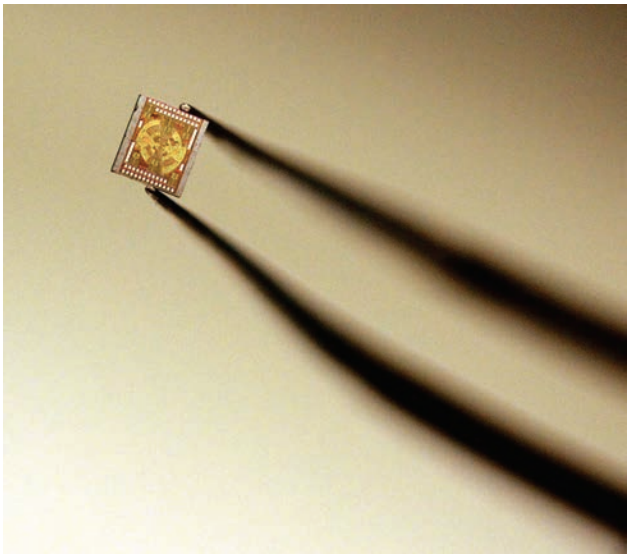
Now, researchers at Princeton University (Princeton, NJ) have drastically shrunk much of that equipment, moving from a tabletop setup with lasers and mirrors to a pair of microchips small enough to fit on a fingertip.

In two papers recently published in the *IEEE Journal of Solid-State Circuits*, the researchers describe one microchip that can generate terahertz waves, and a second chip that can capture and read intricate details of these waves.

"The system is realized in the same silicon chip technology that powers all modern electronic devices, from smartphones to tablets, and therefore costs only a few dollars to make on a large scale," said lead researcher Kaushik Sengupta, a Princeton assistant professor of electrical engineering.

Terahertz waves are part of the electromagnetic spectrum—the broad class of waves that includes radio, x-rays, and visible light—and sit between the microwave and infrared light wavebands. The waves have some unique characteristics that make them interesting to science. For one, they pass through most nonconducting material, so they could be used to peer through clothing or boxes for security purposes, and because they have less energy than x-rays, they do not damage human tissue or DNA.

Terahertz waves also interact in distinct ways with different chemicals, so they can be used to characterize specific substances. Known as spectroscopy, the ability to use light waves to analyze material is one of the most promising—and the most challenging—applications of terahertz technology, Sengupta said.



Fingertip-sized microchip capable of generating terahertz

To do it, scientists shine a broad range of terahertz waves on a target and then observe how the waves change after interacting with it. The human eye performs a similar type of spectroscopy with visible light: We see a leaf as green because light in the green light frequency bounces off the chlorophyll-laden leaf.

The challenge has been that generating a broad range of terahertz waves and interpreting their interaction with a target requires a complex array of equipment, such as bulky terahertz generators or ultrafast lasers. The equipment's size and expense make the technology impractical for most applications.

Researchers have been working for years to simplify these systems. In 2016, Sengupta's team reported a way to reduce the size of the terahertz generator and the apparatus that interprets the returning waves to a millimeter-sized chip. The solution lies in reimagining how an antenna functions. When terahertz waves interact with a metal structure inside the chip, they create a complex

distribution of electromagnetic fields that are unique to the incident signal. Typically, these subtle fields are ignored, but the researchers realized that they could read the patterns as a sort of signature to identify the waves. The entire process can be accomplished with tiny devices inside the microchip that read terahertz waves.

"Instead of directly reading the waves, we are interpreting the patterns created by the waves," Sengupta said. "It is somewhat like looking for a pattern of raindrops by the ripples they make in a pond."

Daniel Mittleman, a professor of engineering at Brown University, said the development was "a very innovative piece of work, and it potentially has a lot of impact." Mittleman, who is the Vice Chair of the International Society for Infrared Millimeter and Terahertz Waves, said scientists still have work to do before the terahertz band can begin to be used in everyday devices, but the developments are promising.

"It is a very big puzzle with many pieces, and this is just one, but it is a very important one," said Mittleman, who is familiar with the work but had no role in it.

On the terahertz-generation end, much of the challenge is creating a wide range of wavelengths within the terahertz band, particularly in a microchip. The researchers realized they could overcome the problem by generating multiple wavelengths on the chip. They then used precise timing to combine these wavelengths and create very sharp terahertz pulses.

In the paper "Dynamic Waveform Shaping with Picosecond Time Widths," published December 14, 2016, in the *IEEE Journal of Solid-State Circuits*, the researchers explained how they created a chip to generate the terahertz waves. The next step, the researchers said, is to extend the work farther along the terahertz band. "Right now we are working with the lower part of the terahertz band," said Xue Wu, a Princeton doctoral student in electrical engineering and an author on both papers.

"What can you do with a billion transistors operating at terahertz frequencies?" Sengupta asked. "Only by reimagining these complex electromagnetic interactions from fundamental principles can we invent game-changing new technology."

The other paper, "On-Chip THz Spectroscope Exploiting Electromagnetic Scattering with Multi-Port Antenna," was published September 2, 2016, in the *IEEE Journal of Solid-State Circuits*. The research for both papers was supported in part by the National Science Foundation's Division of Electrical, Communications, and Cyber Systems (Grant No. ECCS-1408490 and ECCS-1509560).

NOTEWORTHY NEWS

ITC 2017

The International Test Conference (ITC) will be held **October 31 to November 2, 2017,** at the Fort Worth Convention Center in Fort Worth, Texas. ITC is the world's premier conference dedicated to the electronic test of devices, boards, and systems and covers the complete cycle from design verification and validation, test, diagnosis, failure analysis, and back to process, yield, reliability, and design improvement. At ITC, test and design professionals can confront the challenges the industry faces and learn how these challenges are being addressed by the combined efforts of academia, design tool and equipment suppliers, designers, and test engineers.

ITC, the cornerstone of TestWeek events, offers a wide variety of technical activities targeted at test and design theoreticians and practitioners, including formal paper sessions, tutorials, panel sessions, case studies, a lecture series, commercial exhibits and presentations, and a host of ancillary professional meetings.

ITC is sponsored by the IEEE. For more information, visit itctestweek.org.

TRAINING CALENDAR

Rose M. Ring, Qorvo, Inc.
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SEMICONDUCTOR ONLINE TRAINING

EDFAS offers online training specialized for semiconductor, microsystems, and nanotechnology suppliers and users. These online training courses are designed to help engineers, technicians, scientists, and managers understand each of these dynamic fields. This one-year subscription provides access to several courses covering semiconductor failure analysis, design, packaging, processing, technology, and testing. Find out more by visiting edfas.org and clicking on Education.

May 2017

EVENT	DATE	LOCATION
Defect-Based Testing	5/3-4	Munich, Germany
Failure and Yield Analysis	5/8-11	Munich, Germany
Semiconductor Reliability and Qualification	5/15-18	Munich, Germany
Semiconductor Statistics	5/22-23	Munich, Germany
Contact: Semitracks, Inc.		
Advanced Metallographic Techniques	5/8-11	Novelty, OH
Introduction to Metallurgical Lab Practices	5/15-17	Novelty, OH
Contact: ASM International		
Advanced Topics in Light Microscopy	5/16-17	Sydney, Australia
Introduction to Transmission Electron Microscopy (Biological Science)	5/23	Sydney, Australia
Introduction to Scanning Electron Microscopy	5/31	Sydney, Australia
Contact: AMMRF		

June 2017

EVENT	DATE	LOCATION
Introduction to SEM and EDS for the New SEM Operator	6/4	Bethlehem, PA
Focused Ion Beam (FIB): Instrumentation and Applications	6/5-9	Bethlehem, PA
Scanning Electron Microscopy and X-Ray Microanalysis	6/5-9	Bethlehem, PA
Problem Solving: Interpretation and Analysis of SEM/EDS/EBSD Data	6/5-9	Bethlehem, PA

June 2017 (cont'd)

EVENT	DATE	LOCATION
Quantitative X-Ray Microanalysis: Problem Solving Using EDS and WDS Techniques	6/5-9	Bethlehem, PA
Scanning Transmission Electron Microscopy: From Fundamentals to Advanced Applications	6/5-9	Bethlehem, PA
Contact: Lehigh Microscopy School		
Metallographic Techniques Blended (Lab Session)	6/5-6	Novelty, OH
Metallurgy for the Non-Metallurgist Blended	6/13-14	Novelty, OH
Corrosion	6/13-16	Novelty, OH
Contact: ASM International		
Wafer Fab Processing	6/5-8	Portland, OR
Contact: Semitracks, Inc.		
Introduction to Transmission Electron Microscopy (Physical Science)	6/23	Sydney, Australia
Mass Spectrometry	6/24-28	Sydney, Australia
Optical and Confocal Microscopy	6/24-28	Sydney, Australia
Scanning Electron Microscopy	6/24-28	Sydney, Australia
Contact: AMMRF		

July 2017

EVENT	DATE	LOCATION
Energy-Dispersive X-Ray Microanalysis Systems	7/8-12	Sydney, Australia
XRD	7/15-19	Sydney, Australia
Transmission Electron Microscopy	7/22-26	Sydney, Australia
Contact: AMMRF		
Medical Device Design Validation and Failure Analysis	7/27-28	Novelty, OH
Contact: ASM International		

August 2017

EVENT	DATE	LOCATION
Metallurgy for the Non-Metallurgist Blended	8/1-2	Novelty, OH
Metallographic Techniques Blended (Lab Session)	8/7-8	Novelty, OH
Elements of Metallurgy	8/14-17	Novelty, OH
Fractography	8/14-17	Novelty, OH
Contact: ASM International		
Introduction to Light Microscopy	8/22-23	Sydney, Australia
Contact: AMMRF		

Contact Information

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EDFAS AWARDS

Hello EDFAS members,

The call for EDFAS award nominations is now closed for 2017. As chair of the 2017 EDFAS Nominating Committee, I thank all who participated and promoted a colleague for EDFAS Lifetime and President's Awards. Recognizing our peers is a way to show appreciation, strengthen relationships, and build our Society.

Both award recipients receive plaques, and the Lifetime Award recipient will no longer need to pay EDFAS dues to receive member benefits. The award recipients will be announced at ISTFA 2017 in November.

Who do you want to nominate in 2018? It's never too early to start planning. Let's keep the momentum going.

See you at ISTFA!

Best regards,

Cheryl Hartfield
EDFAS Nominating Committee Chair
EDFAS Immediate Past President
cheryl.hartfield@outlook.com

EDFAS MEMBERSHIP

Whether networking at events or accessing information through *EDFA*, ISTFA proceedings, or journals, our members have the edge. Now it's time to introduce EDFAS to others in the industry who would like to take advantage of these career-enhancing benefits. Help us help the industry by expanding our membership and offering others the same exceptional access to information and networking that sets EDFAS apart. To reacquaint yourself with and introduce others to the EDFAS member benefits, visit asminternational.org/web/edfas/membership.

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LITERATURE REVIEW

Peer-Reviewed Literature of Interest to Failure Analysis: Solar Cells, Photovoltaics, and LEDs

Michael R. Bruce, Consultant
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The current column covers peer-reviewed articles published since 2014 on solar cells, photovoltaics, and light-emitting diodes (LEDs). Note that inclusion in the list does not vouch for the article's quality, and category sorting is by no means strict.

If you wish to share an interesting recently published peer-reviewed article with the community, please forward the citation to the e-mail address listed above and I will try to include it in future installments.

Entries are listed in alphabetical order by first author, then title (in bold), journal, year, volume, and first page. Note that in some cases bracketed text is inserted into the title to provide clarity about the article subject.

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- O. Dupré, R. Vaillon, and M.A. Green: **"A Full Thermal Model for Photovoltaic Devices,"** *Sol. Energy,* 2016, *140*, p. 73.
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DIRECTORY OF INDEPENDENT FA PROVIDERS

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Electronic companies of all types and sizes require failure analysis (FA) services. Our goal is to supply a resource of FA service providers for your reference files. The directory lists independent providers and their contact information, expertise, and types of technical services offered.

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GUEST COLUMNIST

BASIC KNOWLEDGE REQUIRED OF AN FA ENGINEER

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INTRODUCTION

Failure analysis (FA) may be the best choice an engineer can make. A career in FA provides continuously challenging projects. Failure analysis also requires detailed knowledge of topics not sufficiently covered by engineering or physics programs. For me, and probably for other analysts, these observations simply explain why failure analysts would not trade jobs with anyone. We can't imagine trading the growth inherent in solving different problems with repetitive jobs or testing or designing similar items.

The ISTFA symposium is a good source of up-to-date FA information that is hard to find anywhere else. The 2016 ISTFA event included a Panel Discussion addressing the required attributes of the "Next Generation of FA Engineer."[1]

The Panel Discussion noted that an FA engineer must have the capability to handle several techniques to localize defects in increasingly complex devices. He/she must be knowledgeable about deprocessing techniques. He/she must understand design, layout, fabrication, test, and application. In addition, communication skills are necessary for interacting with the personnel associated with all the aforementioned areas. Frank Altmann's summary of the Panel Discussion indicated that it provided thoughtful discussion about "the high level of technical knowledge as well as high flexibility and communication skills" required of failure analysts.

The consensus of the Panel Discussion attendees was that a potential analyst requires a daunting list of prerequisites. I must agree, but few, if any, of the best analysts I know enjoyed all of the recommended background. Several lack most of the academic requirements. Clearly, future analysts will have a head start if their academic background includes FA tools and a wider range of related topics.

Perhaps it is too obvious to mention, but the Panel Discussion did not identify problem solving as a necessary part of FA training. Problem solving is a key asset and a strong point for the best analysts I know. There are a few other characteristics that all the best analysts have in common:

1. All have a solid academic foundation in at least a few of the areas listed as being necessary for a future analyst.
2. All have problem-solving basics at the core of their analysis approach. Failure analysis is problem solving. Therefore, basic problem questions—"what, when, where, and how much"—guide every FA.[2]
3. All are motivated to fully understand the theory, mechanics, and limitations of the FA tools they use. They want to understand how the output of the tool applies to the specific sample at hand.
4. This is an extension of No. 3. When limitations of existing FA tools block the progress on an FA problem, all look for ways to extend the capability of the tool. (Consider, for example, backside probing and nanoprobing.)
5. This also is an extension of No. 3. When presented with a possible "cause" or "defect," all delay celebration until the possible cause is verified in some way. At the least, the possible cause must adequately answer the applicable "what, when, where, and how much" questions.

MENTORING

The learning curve of a young failure analyst can be enriched by working with an experienced analyst. Typically, a young engineer brings the latest technology to the team. The experienced mentor provides some hard-to-get perspective.

For example, every new analyst receives the advice "Don't assume." However, the undisputed advice comes without explanation. Actually, analysts assume every day.

Whenever available evidence has two or more equally probable explanations, one is assumed. Additional data

are obtained to verify or reject the assumption. A mentor may explain that "Don't assume" refers to assumptions that are hidden or disguised. The best example comes from physical medicine. "I fell down and broke my hip" hides an assumption. It would be a different problem if the correct language was "My hip broke, and I fell down."

There are many examples from electron FA. "The device failed after two years on the shelf in inventory." An experienced analyst would avoid assumptions and translate this to "The failure was detected after two years in inventory." There is a world of difference. There is no reason to assume the device was "good" when it was put in inventory. There is no reason to assume it was tested after being put in inventory.

This is actually an example in problem definition. "The lot of devices we bought five years ago passed all military standard electrostatic discharge (ESD) requirements. The most recent lot failed to meet ESD requirements. How has the fabrication process changed?" Only after wasting effort on answering the question was the assumption detected. Military standard ESD requirements were in version B. The new lot was tested to version C. Different problem.

There are countless more examples of assumptions that sneak into the "what, when, where, and how much" that define an FA problem.

SUMMARY NOTE

It is a great time to be a failure analyst. There are new, dedicated tools. There are new technologies with associated new challenges. Yet, all the old tools remain important and cannot be forgotten. Surprising new applications for old tools, or modified old tools, appear on a regular basis.

Now more than ever before, failure analysts are recognized for their skill and are appreciated for their contribution. And, now more than ever, *EDFA* magazine, the ISTFA symposium, and local EDFAS chapters offer unprecedented networking benefits.

For those who choose FA as a specialty, welcome. Your successes in solving new problems and advancing the tool base will bring great satisfaction. I have one bit of advice: Share your success by writing for *EDFA* and presenting at ISTFA. The FA community and your career will benefit.

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ABOUT THE AUTHOR

David Burgess is a failure analyst and reliability engineer. He developed techniques and taught in those areas at Fairchild Semiconductor and Hewlett-Packard. He is the founder of Accelerated Analysis, a manufacturer and distributor of specialty failure analysis tools. David is the co-author of *Wafer Failure Analysis for Yield Enhancement*. A graduate of Rensselaer Polytechnic Institute and San Jose State University, he is a member of EDFAS and has served on various ISTFA committees. David is a Senior Life Member of IEEE and was General Chairman of the 1983 International Reliability Physics Symposium (IRPS).

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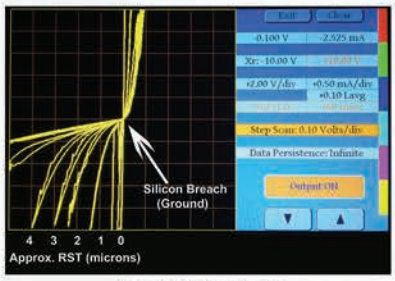

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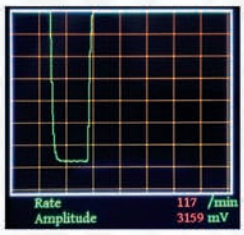

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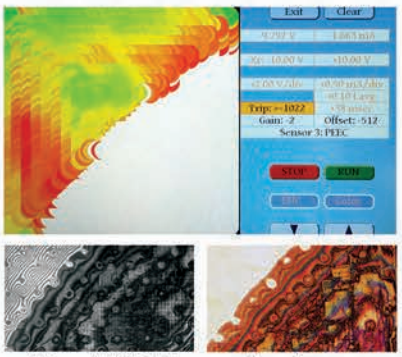

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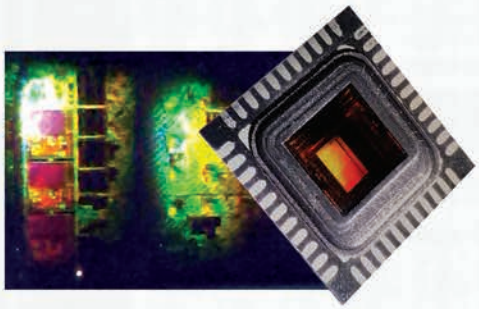

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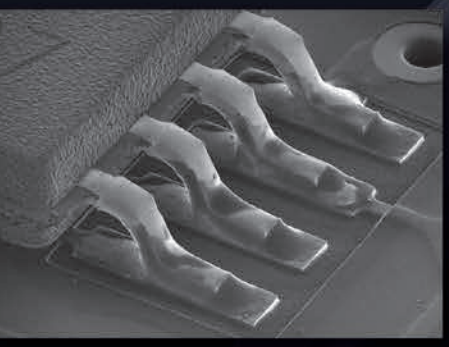
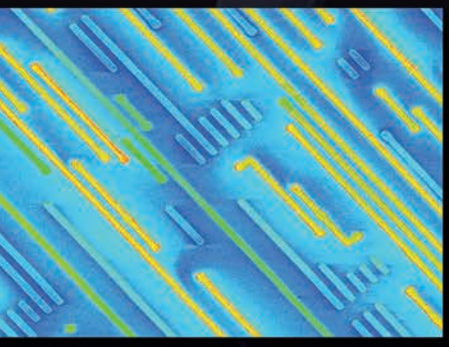
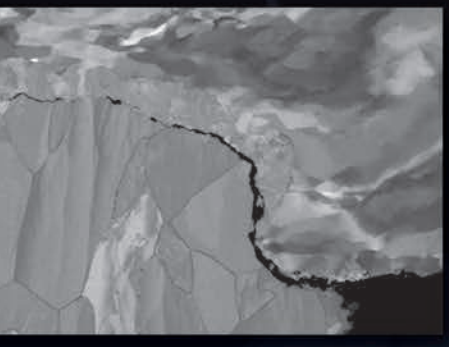
TO YOUR FAILURE ANALYSIS QUESTIONS WITH



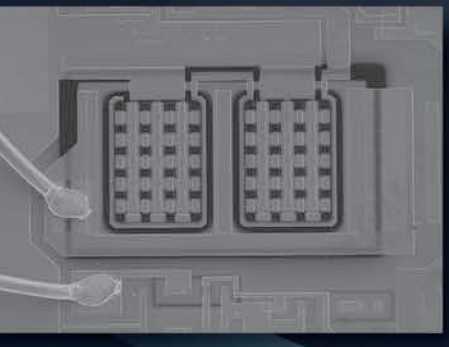
SEM Image of Semiconductor Device



Passive Voltage Contrast (PVC)
image of semiconductor device



Backscatter Electron (BSE)
image of Wire Bond Cross Section



Electron Beam Induced Current (EBIC)
Image of Semiconductor Device

SMART
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POWERFUL

SEM

Questions about...

- *Fatigue?*
- *Corrosion?*
- *Fracture?*
- *Delamination?*
- *Layer Integrity?*
- *Interfaces?*

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