Synopsis: Growing Whiskers

NASA Electronic Parts and Packaging (NEPP) Program

Electrostatic Theory of Metal Whiskers

V. G. Karpov
Phys. Rev. Applied **1**, 044001 (2014)
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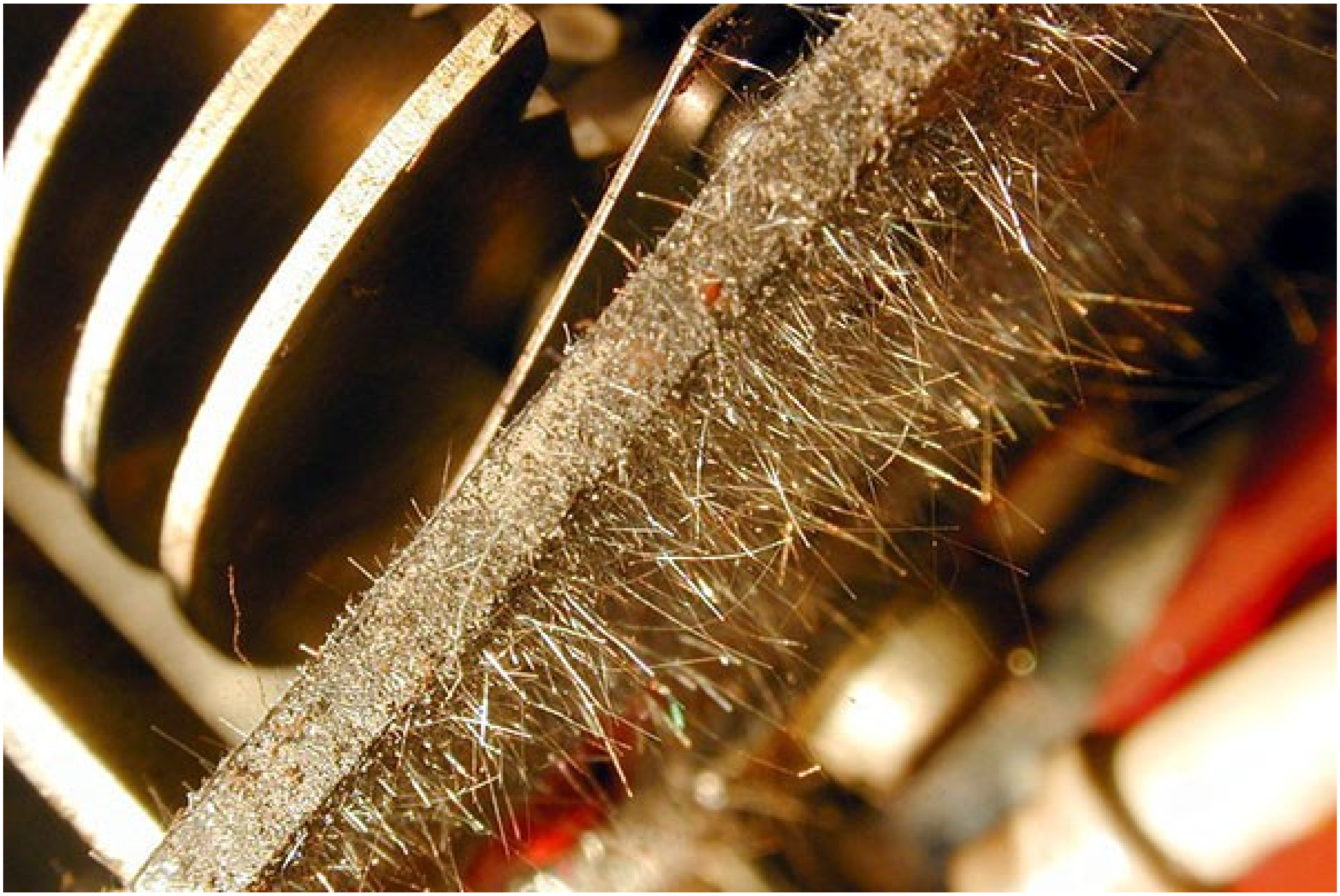
Various metals widely used in electronics, such as tin and zinc, often show hairlike protrusions on their surfaces. These “whiskers” can be responsible for current leakage and short circuits in electronic equipment, causing billion-dollar losses in the auto, aviation, and space industries. But the formation mechanism of whiskers has remained a mystery for over 60 years and researchers have been unable to provide even order-of-magnitude predictions of whisker parameters.

Previous theories offered a qualitative explanation of the growth of a whisker, based on the gain in energy due to the whisker’s needlelike structure. Now, Victor Karpov at the University of Toledo, Ohio, has proposed a theory that provides, for the first time, quantitative estimates of whisker nucleation, growth rates, and length distributions. Karpov, as reported in Physical Review Applied, derived a theory of whisker evolution based on equations describing how local electric fields originating from defects or contaminations in the proximity of a metallic surface can trigger whisker nucleation. The calculations revealed that whiskers evolve through a nucleation stage, a slow growth period, a faster growth period, and a phase of winding or kinking. The observed whisker statistics are related to the randomness of electric fields generated by charge patches on imperfect metal surfaces.

Karpov’s analysis delivers estimates of whisker parameters that are generally consistent with observations and explains many aspects of whisker growth and morphology. Further research will be needed to understand other open questions, such as how whiskers interact with each other to limit or promote their growth. The development of more reliable models of whisker evolution will be useful not only for microelectronic technologies, but also for large-area photovoltaics, where whiskers acting as shunts can cause device failures. – Katherine Kornei



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ScienceShot: How to Shave Metal Whiskers

By Thomas Sumner (/author/thomas-sumner) | Friday, May 23, 2014 - 1:45pm

A whisker can be a wicked thing. In 2005, a Connecticut nuclear power plant shut down after a short-circuited pressure sensor triggered a false alarm. The culprit was a solitary metal whisker thinner than a human hair that sprouted inside the sensor's electronics. Metal whiskers, such as those pictured above, have incapacitated four satellites and short-circuited more than $10 billion in electronics since their discovery in the 1940s, yet until now the mechanism behind whisker formation remained a mystery. This month in *Physical Review Applied*, physicist Victor Karpov of the University of Toledo in Ohio presents the first theory that quantitatively explains how metal

[whiskers form (http://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.1.044001)](http://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.1.044001)
. According to Karpov, imperfections on metal surfaces can form small patches of net positive or negative electric charge. The similar charges repel one another, producing an outward stress. Where the material is weak enough, metal whiskers can grow up to 1 centimeter a year. Karpov suggests that treating metal surfaces with electrolytes, which contain free-moving charges, could neutralize these electrically charged patches, thwarting the growth of any wicked whiskers.

CONVERSATIONS WITH SCIENTISTS

Victor G. Karpov: Tackling Theoretical Physics

July 2014

Courtesy of Victor Karpov

"Don't be afraid to be different: having a different point of view is psychologically stressful, yet your future scientific career won't be of much value if you can't stand the stress."

Victor G. Karpov is a professor of physics at the University of Toledo in Ohio. Born in the former Soviet Union, Karpov earned his Ph.D. in solid state physics in 1979 from Leningrad Polytechnical Institute (known since 2002 as St. Petersburg State Polytechnical University) and completed his Doctor of Sciences in theoretical physics in 1986 at the Soviet Academy of Sciences's Institute for Nuclear Physics. Since joining the Toledo faculty, Karpov has published numerous papers in peer-reviewed physics journals, including the Journal of Applied Physics *and* Physical Review. *Most recently, Karpov co-authored a textbook,* Physics of Thin-Film Photovoltaics.

Karpov's research focuses on "condensed matter, semiconductors, and theoretical physics, including disordered systems, phase transitions, thin films, device physics, and photovoltaics." He is largely concerned with reshaping the "physics of thin film photovoltaics," investigating the "physics of phase change processes in response to electric pulses" and discovering "electric (including laser) field induced phase transformations."

Below are Victor Karpov's June 30, 2014 responses to questions posed to him by Today's Science. *Some of the questions deal with how he became interested in science and began his career in theoretical physics, while others address particular issues raised by the research discussed in Explaining Pesky Metal "Whiskers".*

Q. When did you realize you wanted to become a scientist?

A. At the age of 12 or 13.

Q. How did you choose your field?

A. It was chemistry at first (simple experimentation), then mathematics. It turned into physics almost accidentally at the age of 17 as I entered a university program in physics (joining a program in pure math was problematic at that time due to certain anti-Semitic trends in the math school of our city's university). Finally, having combined math and physics, I

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Explaining Pesky Metal "Whiskers"

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became a theoretical physicist by the time I graduated. My Ph.D. (from St. Petersburg State Technical University, Russia) was in the field of condensed matter, based on my theoretical work, and my final degree, that of Doctor of Sciences (habilitation), was in theoretical and mathematical physics (from the Institute for Nuclear Physics of the Academy of Sciences of the USSR).

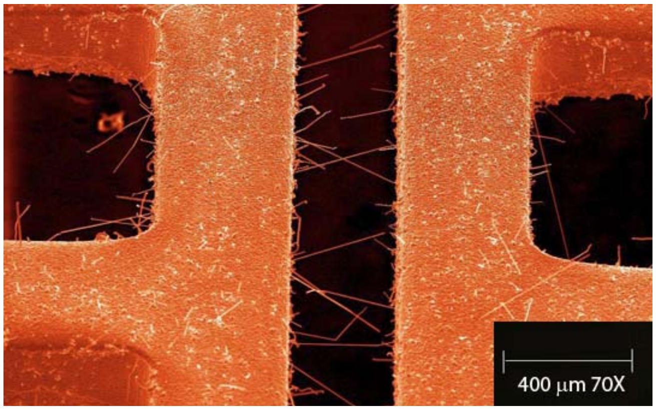
Q. Are there particular scientists, whether you know them in person or not, that you find inspiring?

A. Isaac Newton, Albert Einstein, Louis de Broglie, David Bohm [American theoretical physicist] and many others.

Q. What do you think is the biggest misconception about your profession?

A. That it can be learned by taking classes. In reality, it can be learned only by working on real projects, and, most efficiently, by being guided by someone more experienced and more knowledgeable than you are.

Q. I gather that your explanation of metal whiskers says that free energy considerations make the odds of a whisker forming and/or persisting quite small in the early stages — rather like climbing out of a steep potential well — but, beyond a certain size, the odds shift in favor of the whisker lasting and getting bigger. Is this characterization more or less correct?



Courtesy of Peter Bush (University at Buffalo-SUNY)/NASA

"There exists a critical size, beyond which whiskers are stable and keep growing. And certain physical conditions would tend to increase the odds of whiskers forming."

A. It is correct: there exists a critical size, beyond which whiskers are stable and keep growing. And certain physical conditions would tend to increase the odds of whiskers forming (that is, lower the barriers to formation):

(a) The presence of surface defects and contamination (or oxides) that bring in surface charges.

(b) A “soft” metal surface, i.e., one with low enough surface tension.

(c) High enough motility of surface atoms.

Q. What conditions would tend to make whisker formation less likely?

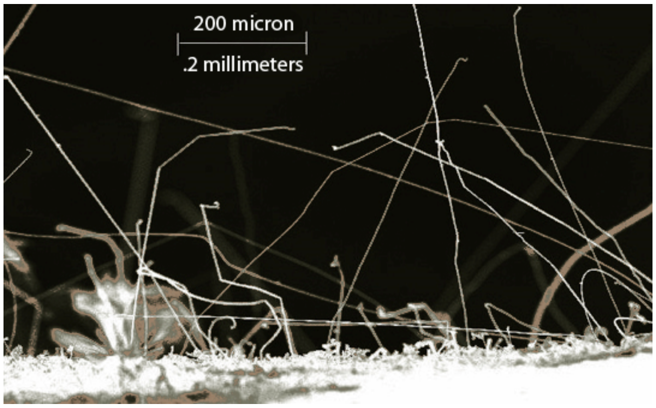
A. Electrical uniformity of the metal surface, such as lack of polycrystallinity or the presence of very large grains (instead of small ones), lack of contamination, diffusion stoppers.

Q. Our story says that the declining use of lead in alloys tends to make whisker formation likelier. Are there (economically viable) substitutes for lead that are less environmentally toxic but can inhibit whisker formation?

A. I am not aware of any confirmed substitutes of that kind.

Q. Do metal whiskers cause problems other than short circuits or issues related to conductivity? Is there anything analogous to the whiskers problem with nonmetallic conductors?

A. Yes, in data centers with many computers, the floors are often zinc plated. After several chemical applications (cleaning soap solutions, etc.), zinc starts growing whiskers. Lifted by mechanical vibrations and workers' feet, these whiskers become airborne and are sucked into the computers by the airflow of fans. There, they cause all kinds of shorts and failures. That is, for example, what caused a shutdown of the Colorado state data center a few years ago.



NASA/NEPP

Whiskers as small as .2 millimeters from the zinc-coated floor tiles of computer-filled server rooms (above) have caused shorts when blown by ventilation systems into the enclosures of the computers themselves.

Also, the potential health effects of whiskers remain unevaluated.

There are nanowhiskers on certain semiconductor crystals (more precisely, there are ways of artificially growing them), but they do not grow spontaneously, and their aspect ratios are much smaller than those for metal whiskers. Also, overall, they are relatively short (in nanometers).

Q. Where do you spend most of your workday?

A. Except for my in-class teaching responsibilities and meetings with students and colleagues, most of my time is spent at my home office desk in front of a computer. The workday concept does not exactly apply: my work extends over nights and weekends very often.

Most of the time, I work on my own; grad student participation is included if possible. Occasionally, collaborations with colleagues, especially with experimentalists, turn out to be very productive.

Q. What do you find most rewarding about your job? What do you find most challenging about your job?

A. What is truly rewarding is that getting to understand things through theoretical physics creates order (established relations) out of disorder (chaotic empirical knowledge). In that sense, a theoretical physicist acts like

God, who created order by separating light from dark, etc. Nothing is more rewarding than the possibility of occasionally understanding something.

The most challenging thing is maintaining a balance between the self-confidence needed to proceed in terra incognita and the humility that enables one to admit mistakes and start over.

Q. What has been the most exciting development in your field in the last 20 years? What do you think will be the most exciting development in your field in the next 20 years?

A. Unfortunately, in theoretical physics, things have not been as exciting in the last 20 years as they were in the last 100 years. But that assessment may be a matter of personal taste.

I hope the most exciting development in my field will come unexpectedly.

Q. How does the research in your field affect our daily lives?

A. Many of my results are in applied physics, and they affect our daily lives through certain patented findings or by switching the mode of thinking in engineering communities. For example, our team was lucky to introduce a concept of self-healing of lateral nonuniformities in large-area photovoltaic modules. Curiously red wine was the first treatment of that kind (the red wine effect as it is now widely known). [For more details, see www.renewableenergyworld.com/rea/news/article/2004/04/red-wine-leads-ut-scientists-to-juice-up-potency-of-solar-cells-11055.]

Later on, this technique was patented, and the patent was licensed exclusively to a major photovoltaic manufacturer. This is a typical example: work started with conceptualization, then experimentation, then industrial implementation.

Q. For young people interested in pursuing a career in science, what are some helpful things to do in school? What are some helpful things to do outside of school?

A. 1. Try the hard way: solve problems and spend time on home assignments. By doing so, you become more capable of concentrating on things for longer periods of time than ordinary people can.

2. Try to get involved with real science, not some toy problems designed for kids; there are no kids in science.

3. Don't be afraid to be different: having a different point of view is psychologically stressful, yet your future scientific career won't be of much value if you can't stand the stress.

4. As much as possible, get involved in sports: being in good physical shape is essential to doing science.

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Explaining Pesky Metal "Whiskers"

by Abe Sorber | July 2014

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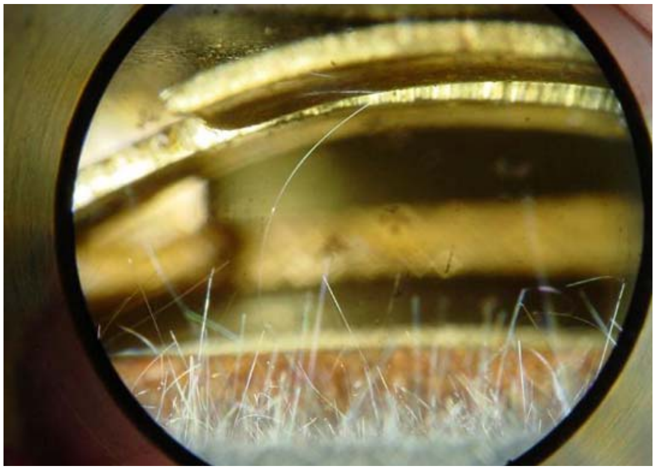
Chances are you've seen a circuit, an assortment of metal components linked by wires or traces on a circuit board. Such devices seem quite durable, but there are certain gremlins that delight in disabling them. They are metal whiskers, hair-like tendrils that sprout on their own from electronic parts, sometimes creating short circuits that lead to breakdowns. Among their most alarming feats so far are causing a sensor at a nuclear power plant to give erroneous readings and turning a handful of telecommunications satellites into space junk, but they have the potential to affect just about any electronic device.



Alan Douglas/UK Vintage Radio Forum/NASA

Metal whiskers, hair-like tendrils that sprout on their own from electronic parts, sometimes creating short circuits that lead to breakdowns. Some of the alarming things they have been known to do include causing a sensor at a nuclear power plant to give erroneous readings and turning a handful of telecommunications satellites into space junk, but they have the potential to affect just about any electronic device. ABOVE: Metal whiskers sprout from a potentiometer, a device used for measuring and regulating electric voltage in audio equipment.

Although scientists and engineers have known about whiskers since at least the 1940s, why they form has remained a puzzle. Meanwhile, a combination of factors is making metal whiskers more threatening and more likely to occur. Electronics are smaller and more central to our lives than ever, while lead — one metal commonly used to reduce the likelihood of whiskers — has already been banned from most consumer electronics in the European Union.

In an effort to address these problems, a scientist has come up with a new theory for why these devilish whiskers grow. Physicist Victor G. Karpov of the University of Toledo in Ohio has proposed that tiny "patches" of charge on metal surfaces promote whisker growth; encouragingly, the theory's predictions roughly match measurements of actual whiskers. Karpov's work

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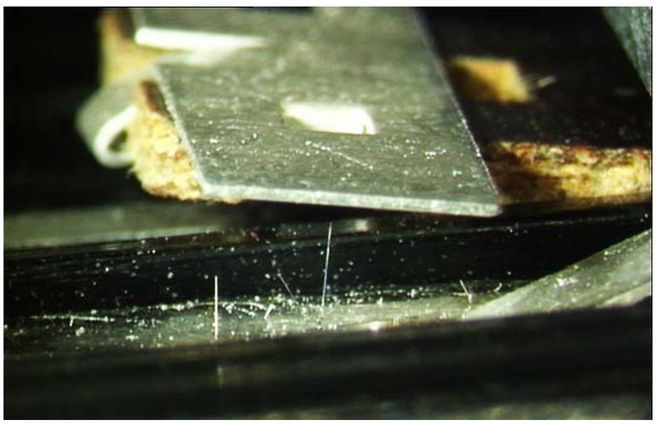
Victor G. Karpov: Tackling Theoretical Physics

Victor G. Karpov is a professor of physics at the University of Toledo in Ohio. Born in the former Soviet Union, Karpov earned his Ph.D. in solid state physics...

was published in the May 15, 2014 issue of the journal *Physical Review Applied.*

A "Short" History

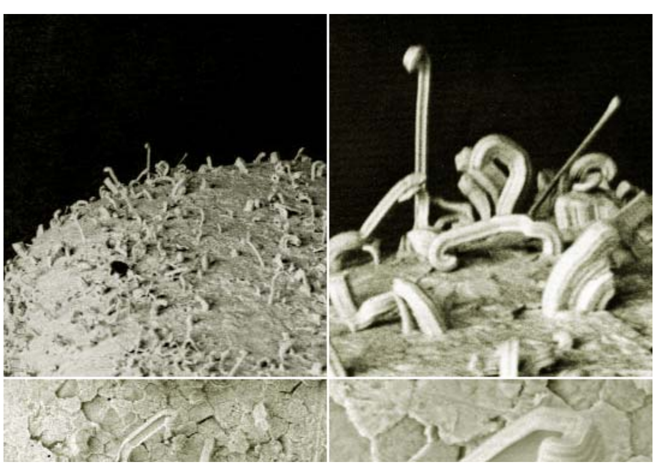
One of the main ways in which whiskers can damage or disrupt electronics is by creating short circuits. Shorts occur when a growing whisker makes contact with another piece of metal, such as a neighboring wire, or when a whisker breaks off and relocates so that it connects two metal parts. Because they are slight, whiskers can only carry about 10 milliamperes (mA) of current before melting. Such thinness might seem like a built-in safeguard, but it has the disadvantage of making failures caused by tin whiskers that melt maddeningly hard to identify. Plus, in the vacuum in which satellites and other space equipment operate, a metal whisker can vaporize and form a plasma, a conducting gas of ions. A plasma can carry much more current than a solid whisker, and can consequently cause far worse damage.

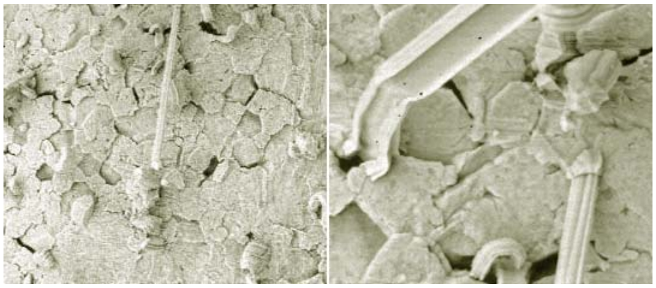


NASA/GSFC

One of the main ways in which whiskers can damage or disrupt electronics is by creating short circuits. Shorts occur when a growing whisker makes contact with another piece of metal, such as a neighboring wire, or when a whisker breaks off and relocates so that it connects two metal parts. ABOVE: Whiskers sprouting from a tin-plated copper contact circuit breaker.

Whiskers are produced by a variety of elements including aluminum, cadmium, gold, iridium, lead, silver, tin and zinc. Tin is one of the worst offenders, because it is highly prone to forming whiskers and is widely used in electronics. It is typically used to coat wire-like "leads" (pronounced as in "leadership") that allow chips and other electronic components to be connected to wires or circuit boards. "Historically, and technologically, tin is the easiest metal to solder," said Karpov, in an email to *Today's Science*.

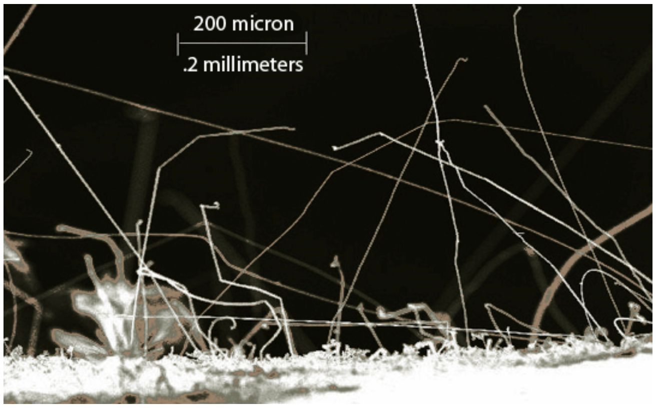




I. Hernefjord/NASA/GSFC

Whiskers are produced by a variety of elements, but tin is one of the worst offenders because it is highly prone to forming whiskers and is widely used in electronics. Tin is typically used to coat wire-like "leads" that allow chips and other electronic components to be connected to wires or circuit boards. ABOVE: Whiskers sprouting from tin-plated terminations used in commercial ceramic chip capacitors.

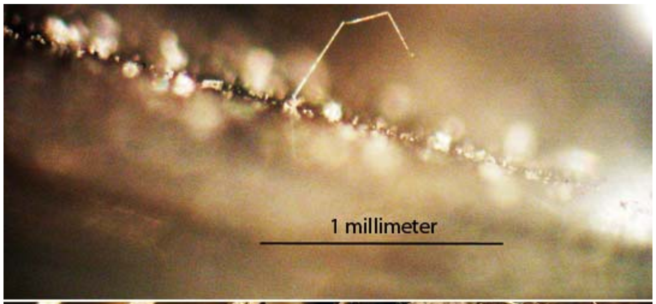
Short circuits from metal whiskers have caused (or have been suspected of causing) various high-profile machine failures. For instance, in 2006, a Connecticut nuclear power plant shut itself down because a tin whisker caused a pressure monitor to report erroneously low readings. In the 1990s and 2000s, several commercial satellites were incapacitated, apparently by tin whiskers disabling the control processors, according to experiments conducted on the ground. More recently, tin whiskers were suspected of being involved in the sudden accelerations that seemed to beset certain Toyota cars. And tin is not the only havoc-wreaking element. For example, whiskers from the zinc-coated floor tiles of computer-filled server rooms have caused shorts when blown by ventilation systems into the enclosures of the computers themselves.

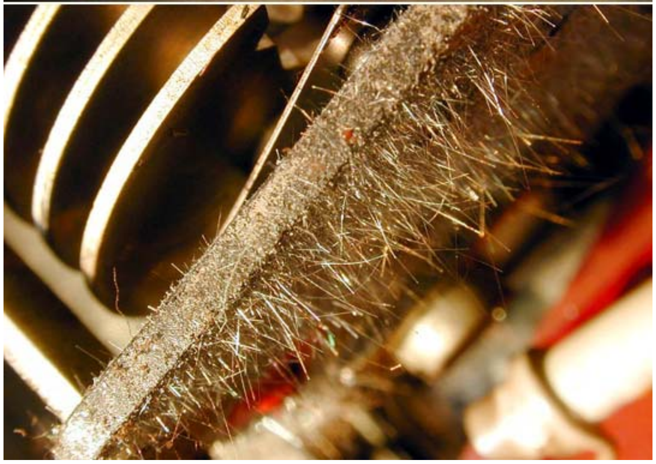


NASA/NEPP

Whiskers as small as .2 millimeters from the zinc-coated floor tiles of computer-filled server rooms (above) have caused shorts when blown by ventilation systems into the enclosures of the computers themselves.

An explanation for these pernicious strands has eluded scientists. It is clear that there is a correlation between whiskers and mechanical stress in metals, either from external forces like bolts or from internal forces trapped within a solidified layer. Beyond that, patterns have been hard to find. Whiskers can develop at a variety of temperatures and humidity levels, and in the presence or absence of electric current. They can spring up just days after the solder has cooled on a new circuit board, or take decades to emerge.





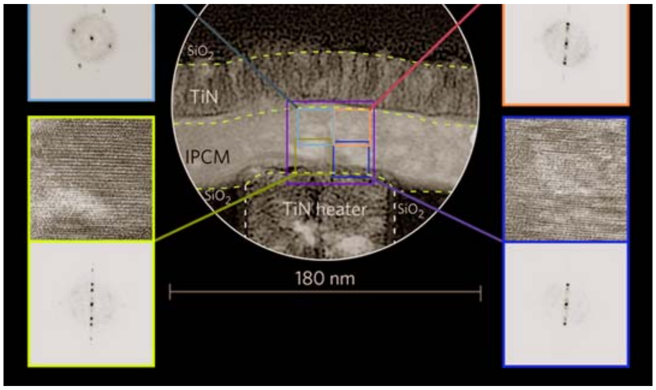
Top: CALCE/University of Maryland/NASA; Bottom: Frank Nikolajsen/NASA/GSFC

Whiskers can develop at a variety of temperatures and humidity levels, and in the presence or absence of electric current. They can spring up just days after the solder has cooled on a new circuit board, or take decades to emerge. TOP: A 1-millimeter whisker sprouts from a relatively new tin-plated USB (universal serial bus) connector used on PC motherboard circuit card assemblies. BOTTOM: Whiskers up to 10 millimeters long crowd the surface of this tin-plated variable air capacitor used in the tuning assembly of a 1960s vintage radio.

We may be experiencing an increase in failures caused by metal whiskers. For one thing, we are relying more and more on electronics, which, as they are miniaturized, become more vulnerable to shorts caused by whiskers. Efforts to remove lead from electronics may also be contributing to an increase in whisker problems. Tin is far less prone to forming whiskers if it's alloyed with lead. As a result, many electronics manufacturers have been using a tin-lead mixture (such as 60% tin to 40% lead by weight) for plating or soldering. Now, though, there is concern that lead from electronic waste might leach into the environment. No restrictions have yet been implemented in the U.S., but, in 2003, the European Union banned all but traces of lead from electronics sold there (with exceptions for non-consumer electronics vital in such areas as transportation, medical technology and space).

A Patchwork of Electric Fields

Karpov encountered metal whiskers because he had been studying the formation of needle-like structures in "phase-change memory," a novel type of memory for digital devices. A cell of phase-change memory can carry information because it has two states, high-resistance and low-resistance. Karpov had discovered that the low-resistance state was enabled by the formation of tiny metallic protrusions, not unlike metal whiskers.



Simpson, R. E., et al./*Nature Nanotechnology*

Victor Karpov encountered metal whiskers because he had been studying the formation of needle-like structures in phase-change memory devices (above). He had discovered that the low-resistance state was enabled by the formation of tiny metallic protrusions, not unlike metal whiskers.

Karpov was searching for other applications for his research when he discovered NASA's metal whisker website. Karpov says he was "literally mesmerized" by the images he saw there. "However," he adds, "I became still more motivated having learned that metal whiskers, known for sixty-plus years and having caused billions of losses to industry, remained a mystery."

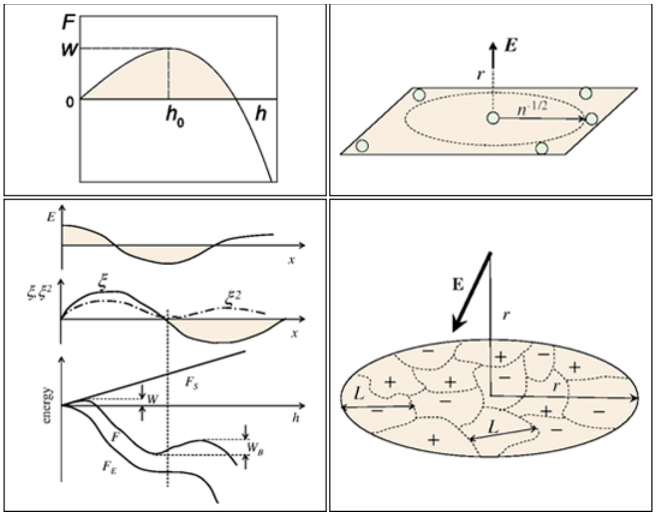
In Karpov's theory, metal whiskers, like the needle structures in phase-change memory, are caused by electric fields. If you've seen a rubber balloon attracting the hair on someone's head, you've seen electric fields in action. They are the nearby regions in which charges, positive or negative, have the power to push or pull on other charges. Karpov's theory of metal whiskers is called an "electrostatic" theory because it is strictly concerned with static electric fields, those that don't change with time. [See Static Electricity—It's Not All About Trapped Electrons, July 2014.]

Specifically, the theory proposes that small, naturally occurring electric fields on the surface of a metal cause whiskers (the addition of external fields, from flowing electricity, could boost this effect). A metal surface, far from being uniformly charged, turns out to be a patchwork of such fields, which are known to come from irregularities in a metal, such as rough spots: areas where individual metal "grains" are oriented differently from those nearby, or places on a metal surface that have been contaminated by foreign molecules or atoms. All these anomalies may cause electrons to be distributed unevenly, creating patches with overall positive or negative charge.

Betting on the Critical Length

From the concept of patches on a surface, Karpov derived equations to predict whisker growth, using well-known principles of math and physics. One such principle, fundamental to Karpov's theory, is free energy. Free energy is the energy in a "system" — a metal surface, a chemical reaction, a pot of boiling water, etc. — available to do work. Systems tend to progress in a way that results in an overall release of free energy. [See Nanonails!, January 2008.] According to Karpov's work, the growth of whiskers ultimately releases free energy, so such growth can be favorable for a metal surface.

In Karpov's theory, there are two competing factors that affect the free energy of a metal surface. On one hand, growing a whisker releases free energy because it permits electrons to migrate to a lower energy position within the electric field of nearby patches. For instance, moving to the end of a whisker might give some electrons a chance to flee the repulsive force of other electrons on the surface. On the other hand, there's a free energy toll taken in forming a new whisker, because a growing whisker increases the surface area of the metal, and atoms need more energy to exist on the surface than within the body of a material.



Karpov, V. G./*Physical Review Applied*

Figures clockwise from top left: 1) Free energy of a metal whisker versus its length. 2) The perpendicular electric field component *E* at small distance *r* from the metal surface. Pale green circles represent point surface charges with the average intercharge distance *n-1/2>r*. 3) The patched area domain of radius *r* where + and - represent positively and negatively charged patches of characteristic linear dimension *L* each. The thick arrow represents the random field vector at distance *r* along the domain axis. 4) The coordinate dependencies of random electric field *E(h)* (top), random functional *?=?0hE(x)dx* and its square (middle), and free energies: surface contribution *FS*, electrostatic contribution *FE*, and their sum *F=FE+FS*. The vertical dashed line marks the point of *?=0* of *FE* flattening that gives rise to a barrier WB blocking the whisker growth.

In Karpov's main equation for free energy, these competing factors are represented by terms with opposite signs. Both terms change value depending on the length of the whisker, but, critically, they change in different ways. For short whisker buds, the term representing the free energy cost due to surface area is bigger; however, for longer whiskers, the term representing the energy payout due to migrated electrons is bigger. This discrepancy means that if a whisker exceeds a certain, critical length, further growth will only decrease the free energy of the system—it's all downhill from there.

Therefore, once a whisker exceeds the critical length, it will become permanent. But how does it actually begin to grow? (The equation for free energy, which represents an overview of the situation, cannot say.) It turns out that in the domain of the microscopic, an ordinary event is all that's needed to create a whisker; the continuous, random fluctuations in the shape of the surface will occasionally generate a whisker long enough to be stable. (Karpov estimates the critical length to be about 10 nanometers, or 10 billionths of a meter.)

Physicists tend to take a statistical view of random fluctuations, regarding them as bets being placed in an exceptionally busy casino. Each fluctuation has really poor odds — it's extremely unlikely that one would produce a stable whisker — but they occur so astoundingly often that some occasionally hit the jackpot. "At any given spot, such a significant fluctuation has a probability of roughly 10^{-20} [a decimal point, followed by 19 zeroes, followed by 1) or so," says Karpov, "but the number of attempts is large and the system has enough time to wait." A lottery is another instance of this sort of situation—the odds are slim that a particular person will win, but certainly there are winners—and if you envision a whole lot of lotteries happening, then you end up with a fair number of winners. (If you like this kind of physics, you may find it interesting that Karpov's free energy equation, with its two competing factors, is based on "classical nucleation theory," which is used to explain the formation of bubbles, crystals or droplets during a phase change like boiling or condensation. For example, when a bubble forming in boiling liquid reaches a certain "critical radius," its stability is assured.)

Keep It Cool

Karpov's equations incorporate some quantities that have to be measured or estimated, like the relevant surface tension for a metal, which directly affects the amount of free energy consumed as a whisker grows in surface area. Not all of these quantities are known, but putting in estimates that seem reasonable led to predictions (of whisker growth rates, for example) that roughly match observations in previous metal whisker studies. Another reassuring sign is that, although it's based on electric fields, Karpov's theory is compatible with the idea that stress causes whiskers. Stress could create the electric field patches that Karpov's theory requires for whiskers to grow.

One next step will be to test the theory. There are a variety of experiments that Karpov's paper suggests could do the job, such as putting a metal sample inside an electron microscope or doping it with charged nanoparticles. In any case, the idea is to subject the metal surface to an electric field and observe the results. A particular challenge would be to maintain an electric field without causing electricity to flow in the metal. "This is not a trivial experiment, because you want to apply the field and yet avoid electric current that could heat the system up," said Karpov.

Discussion Questions

The initiation of a metal whisker is compared in this article to the formation of objects such as bubbles, crystals and raindrops. We know that certain conditions can change the likelihood of such things forming (e.g., turning up the heat under a pot of water, or higher humidity when it comes to raindrops). Does this have implications for metal whiskers? Can you think of other examples that might fit in with "nucleation theory"?

Journal Articles and Abstracts

(Researchers' own descriptions of their work, summary or full-text, on scientific journal websites)

Karpov, V. G. "Electrostatic Theory of Metal Whiskers." *Physical Review Applied*, May 15, 2014: link.aps.org/doi/10.1103/PhysRevApplied.1.044001.

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Metal Whisker Growth Clarified

Hypothesis may help prevent failure of electronic devices

By Jyllian Kemsley

Department: Science & Technology
News Channels: Materials SCENE
Keywords: electronic, whiskers

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So-called whiskers growing out of metal surfaces commonly cause current leaks or short circuits, resulting in electronics failures in satellites, power plants, and even pacemakers. Although reports of whiskers date back to the 1940s, the mechanism behind their growth is poorly understood. The answer may lie in electric field formation just above metal surfaces, according to a theoretical analysis by Victor G. Karpov of the University of Toledo (*Phys. Rev. Appl.* 2014, DOI: 10.1103/physrevapplied.1.044001). Metal surface defects, such as oxide formation, chemical contamination, local stresses, or interfacial boundaries, can generate a strong electric field within 1 µm of the surface. That electric field induces nucleation of needle-shaped metal filaments, about 100 nm long and 1 nm in diameter, Karpov suggests. Electric fields may also influence whiskers' growth rates, lengths, and diameters, as well as how many appear in a particular location. Previous observations indicate that whiskers grow from their bases by adding material obtained through long-range surface diffusion. More work is necessary to determine the chemical nature of whisker development and how whiskers correlate with specific surface imperfections.

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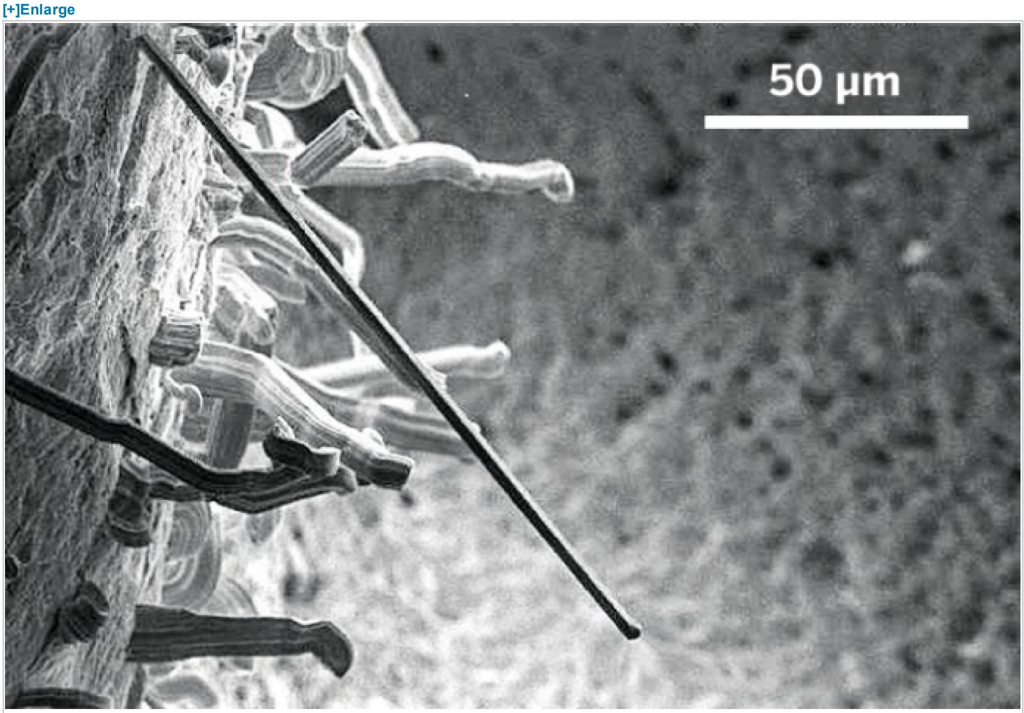

Tin whiskers grow on a capacitor.

Credit: Courtesy of NASA

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INSIDE SCIENCE NEWS SERVICE

New Theory Explains Mysterious Growth of Metal Strands

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Metal whiskers wreak havoc on electronics, but their origin has remained unknown.

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By: Marcus Woo, Contributor

(Inside Science) -- They're but a wisp of metal, hardly noticeable to the human eye. Yet they've crippled everything from pacemakers and watches to missile systems and satellites.

Although these seemingly innocuous metal strands, which appear in electronics, have been wreaking havoc for more than 60 years, no one knows exactly how they form.

But one physicist now says he may have an idea. If he's right, his theory could lead to a better way to prevent such damage, which he says has been estimated to cost billions of dollars.

These strands, called whiskers, were discovered when they disabled aircraft radios during World War II. They sprout from what were once smooth surfaces of metals like tin, zinc, and cadmium, and when they grow in electronics, the strands can touch nearby electrical components and trigger short circuits. Although they are usually less than a millimeter long, they have been known to reach 10 millimeters.

Whiskers, which are ten to a hundred times thinner than human hair, have been blamed for a myriad of electrical failures. Most recently, they were implicated as a possible cause of the sudden, unintended acceleration of Toyota vehicles. In 2011, however, a NASA Engineering and Safety Center report for the National Highway Traffic Safety Administration could not demonstrate that tin whiskers were the culprits of high-speed accelerations and brake failures.

Citing the report, Toyota has said whiskers were not responsible. But the strands, which were found in defective accelerator pedals, aren't completely exonerated, said Henning Leidecker, a physicist at NASA's Goddard Space Flight Center in Greenbelt, Maryland, who was a part of the investigation of unintended acceleration. In fact, he said, the report found that whiskers triggered slower-speed accelerations that reached 20 to 35 mph, although the brakes were able to reduce the speed.

To mitigate the damage brought on by whiskers, engineers have tried special coatings that stunt whisker growth or avoiding the most susceptible metals altogether. "People don't really understand why they grow," said Victor Karpov of the University of Toledo in Ohio. "They don't know how to universally beat them."

Previously, researchers suspect that stress on the metal creates the whiskers, Karpov said. But there was no real explanation for why this should happen.

Now Karpov said he has what may be a better theory. According to his idea, which he published last week in the journal *Physical Review Applied*, whiskers do not sprout directly from mechanical stress, but from electric fields created by the metal itself.

Stress or defects can produce patches of positive and negative electric charges on the metal's surface, Karpov explained. Each patch generates an electric field that repels anything with the same charge. And since the patch is filled with bits of metal of the same charge, some of that metal is expelled, shooting out in the form of a needle-like strand.

"This is the first time this mechanism has been proposed as far as I know," said Leidecker, who wasn't a part of Karpov's work. "It's a mechanism that's consistent with the laws of physics. I don't know of a physical reason against it, so I think it's worth exploring."

While more work remains to further test, develop, and refine the theory, it does make several predictions, Karpov said. For one, the theory predicts that a whisker would first grow slowly, but after about a month or so, it would sprout very quickly — which is exactly what happens in reality. The theory is also consistent with the fact that a variety of factors ranging from stress to contaminants in the metal can lead to whisker growth.

Karpov admitted that many questions remain. For example, his theory can't yet describe whisker growth down to the detail of individual metal grains. And, as Leidecker pointed out, it doesn't explain why some metals are prone to more whiskers than others.

To test the theory, Karpov plans to grow whiskers in a strong electric field, which should greatly affect how they grow. One experiment won't be convincing enough, but if the theory ultimately proves correct, then it could be a boon for preventing whisker damage.

"If I'm right, and there are random charges sitting on the metal surface, there might be a way to neutralize them," Karpov said. One way to neutralize the charges is to spray the metal with a liquid that contains positively and negatively charged nanoparticles. The nanoparticles would be attracted to the oppositely charged patches and neutralize them — and nip the whiskers in the bud.

Marcus Woo is a freelance science writer based in the San Francisco Bay Area who has written for National Geographic News, New Scientist, and other outlets.

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Electrostatic Theory of Metal Whiskers

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Abstract

The nature of metal whiskers remains a mystery after several decades of research. No single pattern has been established to explain the observed whisker correlations with structural defects, mechanical stresses, and contaminations. Here, it is proposed that the electric charges on metal surfaces and their induced local electric fields can present such a pattern. These charges can be produced by various factors, such as surface imperfections, contaminations, oxide states, grain boundaries and random orientations of grains in the polycrystalline surface, and external or internal mechanical stresses (through the deformation potential). The sign of such surface charges varies between different locations (i. e. the electrons are redistributed nonuniformly) forming a random chess board of negatively and positively charged patches with the characteristic linear dimensions in the range of microns. From the energy point of view, the existence of metal whiskers is attributed to the energy gain due to electrostatic polarization of metal filaments in the near surface electric field. In other words, the filaments arise because similar charges repel one another, producing an outward stress. Some of these like charges are expelled upward by creating metal whiskers. This process can be described as the electrostatically driven filament nucleation; it can be especially efficient where the material is locally weak. Following nucleation is the whisker growth stage. It is shown that whiskers first grow at extremely slow rates which accelerate drastically and then remain time independent as the whisker lengths exceed the characteristic linear

dimension of the charge patches. Beyond that length, the whisker growth is affected by random fields of the neighboring patches. In some regions, such fields create energetically unfavorable electric polarization that prevents further growth. The statistics of such unfavorable regions calculated in the proposed theory determines the probabilistic distribution of whisker lengths; it is shown to be approximately log-normal. Overall, the proposed theory provides closed form expressions and quantitative estimates for the whisker nucleation and growth rates and the range of whisker parameters. Many questions remain open. For example, this theory can't yet describe the materials science aspects, such as whisker growth down to the detail of individual metal grains and why some metals are prone to more whiskers than others; neither has it described inter-whisker interactions and their 3D evolution in random electric fields.

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Figure Legend:
Tin whiskers on (matte) tin-plated copper alloy lead-frames used for integrated circuit (IC) terminations. Courtesy of Peter Bush (University of Buffalo-SUNY)