Rectennas Revisited

Mario Bareiß, Peter M. Krenz, *Member, IEEE*, Gergo P. Szakmany, Badri N. Tiwari, Daniel Kälblein,
Alexei O. Orlov, Gary H. Bernstein, *Fellow, IEEE*, Giuseppe Scarpa, Bernhard Fabel, Ute Zschieschang,
Hagen Klauk, *Member, IEEE*, Wolfgang Porod, *Fellow, IEEE*, and Paolo Lugli, *Fellow, IEEE*

***Abstract*—In the late 1960s, a new concept was proposed for an infrared absorbing device called a "rectenna" that, combining an antenna and a nanoscale metal–insulator–metal diode rectifier, collects electromagnetic radiation in the terahertz regime, with applications as detectors and energy harvesters. Previous theories hold that the diode rectifies the induced terahertz currents. Our results, however, demonstrate that the Seebeck thermal effect is the actual dominant rectifying mechanism. This new realization that the underlying mechanism is thermal-based, rather than tunneling-based, can open the way to important new developments in the field, since the fabrication process of rectennas based on the Seebeck effect is far simpler than existing processes that require delicate tunnel junctions. We demonstrate for the first time the fabrication of a rectenna array using an efficient parallel transfer printing process featuring nearly one million elements.**

***Index Terms*—Antenna arrays, infrared (IR) detectors, rectifiers.**

I. INTRODUCTION

NUMEROUS groups [1]–[34] since the sixties have been working in the field of antennas coupled to metal–insulator–metal (MIM) diodes, namely rectennas, for absorbing infrared (IR) radiation. The MIM diode is a quantum device in which a nanometer-thick dielectric, often an oxide, is sandwiched between two electrodes featuring dissimilar work functions. The dissimilarity in the work functions is thought to cause an asymmetric tunnel current to flow through the oxide with respect to the polarity of the electrodes. According to the existing theory, the MIM diode is coupled in parallel to the antenna, so the high-frequency terahertz currents induced in the antenna under illumination are partially rectified by the MIM diodes. Theory holds that using dissimilar work functions for the electrode metals enables rectenna operation without the need for an externally applied bias, which would be the case for energy harvesting. Also, for rectennas as IR detectors, the antenna response may be increased by biasing the MIM diode with a constant external voltage, in which case the two electrodes may have the same work function.

Currently, several groups are working on theory and experiments to design the "ultimate" rectenna suitable for industrial applications, such as energy harvesting and IR detection [26]–[29], [31], [34]. This includes the topic of impedance matching in order to extract electrical currents efficiently without having high losses [33]. In this paper, we use two complementary approaches, namely an antenna array fabricated by a novel nanotransfer-printing process, discussed below, and individual antennas fabricated by electron-beam lithography and lift-off techniques to demonstrate that the Seebeck effect is the dominant rectification mechanism in rectennas, in contradiction to the established view that attributes signal response to the rectification of MIM diode currents. By eliminating the need for the tunnel barrier, our finding leads to a significant simplification of the design and fabrication of rectennas and, therefore, brings a major breakthrough in rectenna applications for IR detectors, solar cells and energy harvesting devices.

Moreover, we present the first rectenna array featuring almost 1 million dipole antennas, coupled to nanometer-size MIM junctions, which we will show function due to thermal rather than tunneling effects. We report here the response of several sub-assemblies of antenna-coupled MIM diodes to incident IR radiation. Further, the optoelectronic characteristics of single antennas and arrays of antennas were simulated [35] and tested to minimize destructive interference of neighboring antennas. Simulations showed that the signal strength for 10.6 μm radiation was a maximum for antennas spaced about 5 μm apart. By fabricating our rectenna arrays with our highly efficient nanotransfer-printing (nTP) process, we demonstrate that our rectenna arrays can be manufactured at low-cost on virtually any surface.

This paper reports in Section II on the material properties with respect to the MIM diode, and on the antenna array design. The electronic and optoelectronic properties of rectenna arrays are discussed in Section III. In Section IV, the focus is placed on the Seebeck effect. Biased rectennas are discussed in Section IV. A final conclusion is given in the last section (see Section V).

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M. Bareiß, G. Scarpa, B. Fabel, and P. Lugli are with the Institute for Nanoelectronics, Technische Universität München, 80333 Munich, Germany (e-mail: bareiss@nano.ei.tum.de; scarpa@nano.ei.tum.de; fabel@nano.ei.tum.de; lugli@nano.ei.tum.de).

D. Kälblein, U. Zschieschang, and Hagen Klauk are with the Max Planck Institute for Solid State Research, 70569 Stuttgart, Germany (e-mail: D.Kaelblein@fkf.mpg.de; u.zschieschang@fkf.mpg.de; H.Klauk@fkf.mpg.de).

P. M. Krenz, G. P. Szakmany, B. N. Tiwari, A. O. Orlov, G. H. Bernstein, and W. Porod are with the Center for Nano Science and Technology, University of Notre Dame, Notre Dame, IN 46556 USA (e-mail: Peter.Krenz.1@nd.edu; gszakman@nd.edu; btiwari@alumni.nd.edu; aorlov@nd.edu; gary.h.bernstein.1@nd.edu; porod@nd.edu).

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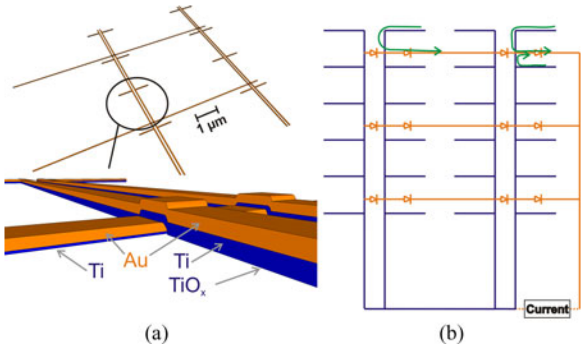


Fig. 1. (a) MIM diodes are formed at the intersections between the Au bottom electrodes (with the Ti adhesion promoter beneath) and the Ti top electrodes (with the 2.2-nm-thick plasma-grown TiO_x dielectric beneath and the Au delamination promoter on top). Each MIM diode is coupled to an antenna (Ti-Au). (b) The resulting circuit diagram shows the lines transferred in the first nTP step (horizontal lines), the antenna structures transferred in the second step (vertical lines including antenna structures) and the path taken by the rectified currents (indicated by the pointers).

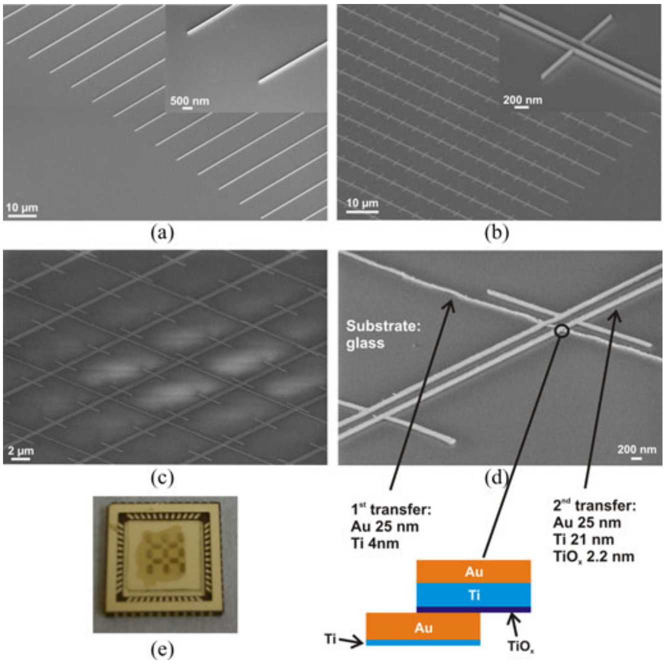


Fig. 2. (a) Scanning electron microscopy (SEM) images of the first stamp and (b) of the second stamp. (c) Magnified view of the rectenna array transferred onto a glass substrate. (d) High-resolution image of the rectenna array, showing the antenna structures and the MIM junctions created at the overlap between the Au bottom electrodes and the Ti top electrodes. (e) Packaged chip including the contact pads fabricated by optical lithography.

II. MATERIAL PROPERTIES AND ANTENNA ARRAY DESIGN

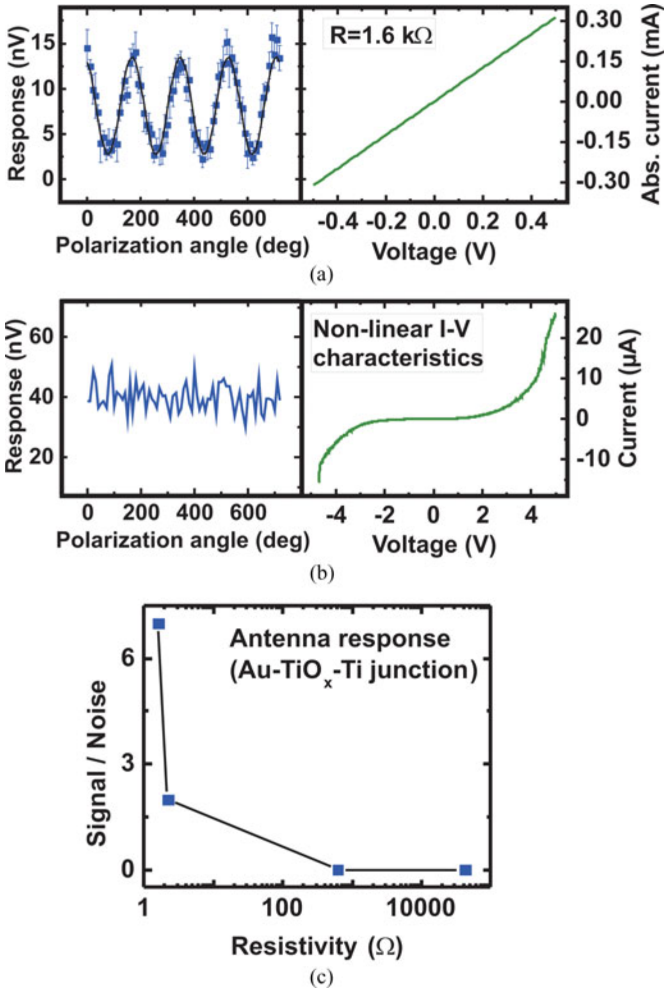
In our previous investigations of the MIM diode phenomenon, we fabricated aluminum (Al) [36], titanium (Ti) [37], gold (Au) [36], and platinum (Pt) [32] as electrode materials and native grown aluminum oxide (AlO_x) [38], plasma-grown AlO_x [36], plasma grown titanium oxide (TiO_x) [37], and self-assembled monolayers (SAMs) as inorganic or organic dielectric materials. Our previous studies [39] showed that organic materials or native oxides as a sole insulator does not form a uniform dielectric layer. At that time, we sought the highest nonlinearities and lowest resistance in the current–voltage $(I\text{–}V)$ characteristics of the diodes, as well as the lowest permittivity of the dielectric. During the investigation of these materials [37], we found that the dielectric permittivity is strongly dependent on the dielectric thickness [36], [37]. The most promising results for overall diode characteristics were obtained with plasma-grown AlO_x (3.6 nm thick) and plasma-grown TiO_x (2.2 nm thick) [37]. Based on our investigations, we chose Ti–TiO_x–Au as the optimum material combination for obtaining nonlinear MIM diode properties.

Previously, we fabricated only individual rectennas [30]. However, in order to consider a device for energy harvesting applications, an array of rectennas must be demonstrated. The relative distances between the antennas, as well as the dimensions of the individual antennas, were simulated and optimized for sensitivity to a wavelength of 10.6 μm and to avoid destructive interferences between neighboring antenna elements (see Fig. 1).

A two-step nTP process was designed to efficiently fabricate an array of almost one million dipole antennas, all coupled to MIM junctions. We printed the devices using templates, or "stamps," directly onto a transparent glass substrate that can be easily activated by an oxygen plasma treatment and thus provides a hydrophilic surface. It is important to note that our fabrication process consists of efficient, industry-compatible steps, and does not require repeated long and expensive exposure times. The first stamp, shown in Fig. 2(a), transfers Au bottom electrodes of the MIM diodes in the form of narrow lines onto the glass substrate, with a thin Ti layer that promotes adhesion to the glass surface. The metal antennas and the TiO_x–Ti stacks that form the tunnel dielectric and the top electrodes are then transferred from a second stamp [see Fig. 2(b)], creating antenna-coupled Au-TiO_x–Ti junctions in the overlap areas. The Ti top electrode is covered by a thin Au layer that is needed to facilitate delamination of the TiO_x–Ti stack from the stamp. Fig. 2(c) shows a portion of the antenna array, and Fig. 2(d) shows a single antenna including the MIM junction. This low-cost and high-speed fabrication technique offers a critical advantage over conventional rectenna fabrication by electron-beam lithography. The rectenna arrays fabricated with nTP have a surface that consists only of Au, and thus features excellent properties with respect to the absorption of irradiated radiation [40]. After the fabrication of the array, we define contact pads on top of the array by conventional optical lithography and lift-off techniques in order to characterize individual sectors featuring 25 000 rectennas each. A full chip in a package is shown in Fig. 2(e).

III. ELECTRONIC AND OPTOELECTRONIC PROPERTIES OF THE RECTENNA ARRAY

In order to determine the rectenna response of several sectors of the array, we connected individual sectors (as defined by the bonding pads) to a voltage amplifier, and illuminated the entire array with a linearly polarized CO_2 laser operating at 10.6 μm, i.e., 28 THz. A half-wave plate was used to adjust the orientation of the linear polarization of the incident radiation. We observed



(a)

(b)

(c)

Fig. 3. (a) Polarization-dependent antenna response of a section of the rectenna array that shows linear I–V characteristics with a small resistance. (b) In contrast, the antenna response of a section of the rectenna array that shows high-resistance and exponential current–voltage-characteristics is below the noise level. (c) The highest signal to noise ratio is attained by a sector with lowest resistivity, which supports the model of a thermal rectification effect in the rectenna array.

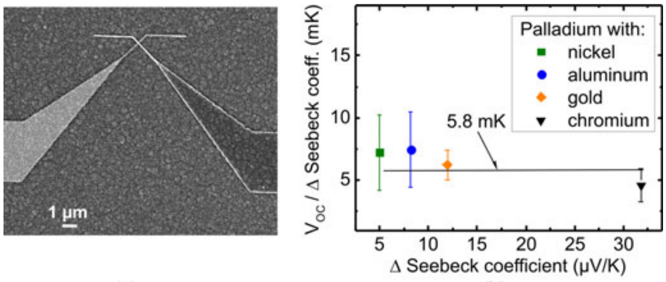
a clear polarization-dependent antenna response in several sectors. When the linear polarization of the incident electric field was perpendicular to the axis of the dipole antennas, the antenna response was near the measureable noise level. When the polarization of the IR wave was parallel to the axis of the antennas, the measured response was seven times larger than the noise level [see Fig. 3(a)]. To our knowledge, an antenna array of this size has never before been demonstrated to produce a signal at THz frequencies. In addition, by optimizing the design of the rectenna array by simulations, we were able to obtain the highest polarization ratio for unbiased rectennas in this wavelength regime. Polarization ratio is defined as the ratio of the antenna response to incident radiation with linear polarization parallel to the antenna axis to that of polarization perpendicular to the antenna axis.

However, other sectors investigated did not exhibit any radiation response. In order to understand this result, we investigated the I–V characteristics of the diode ensembles without illumination. In those sectors where no antenna response was observed, the expected tunnel-diode-like, non-linear I–V behavior was measured, and had a resistance in the range of megaohms. In contrast, we found that the sectors in which we observed a clear antenna response exhibited a linear I–V characteristic with a small resistance (~1 kΩ), that is, the dielectric in several sectors exhibited linear resistive paths rather than tunnel-barrier behavior. These linear resistive paths might occur due to either a defect in the oxide or a mechanical break in the oxide. We believe that the higher noise value in the high-resistance sectors is due to Johnson noise because the Johnson noise is proportional to the resistance [41], [42]. In other words, the observed relationship between the I–V characteristics of the MIM junctions and the measured antenna response is exactly opposite to that expected by the original MIM diode theory. Even when considering surface plasmon polaritons to be present due to IR absorption at the metal–dielectric interface, the tunnel current is not high enough in order to detect a dc signal [43], [44]. This suggests that the operation mechanism of the rectennas is not based on tunneling rectification in the MIM junctions, as was previously thought.

IV. SEEBECK EFFECT VERSUS TUNNELING RECTIFICATION

We believe that the Seebeck effect [45] is the dominant mechanism in our devices that do not exhibit a tunnel barrier, leading to the antenna response. Due to IR absorption, the array is heated up, whereas the electrodes furthest away from the array and closest to the contact pads are not heated. The temperature gradient in each of the electrodes creates a voltage drop, which is related to the Seebeck coefficient of the electrode metals [46]. Further, the Seebeck-effect provides a consistent explanation for the observed relationship between the current–voltage behavior of the sectors of the antenna array and the measured antenna response (quantified by the signal-to-noise ratio) seen in Fig. 3. Devices with a lower resistivity exhibit a larger signal-to-noise ratio [see Fig. 3(c)]. After the fabrication of the device, we characterized parts of the array using a CO_2 laser beam setup. The device under test (DUT) was mounted on a translation stage that can shift the DUT perpendicular to the incident laser beam in order to scan the whole sample. The CO_2 laser is illuminating an area of about 1 mm^2 and the laser is operated at its main emission line at 10.6 μm (28 THz). A polarizer ensures a linear polarization of the emitted light and a half-wave plate can rotate the polarization by 360°. A chopper is modulating the laser beam and the response of the DUT is determined with a lock-in amplifier that is synchronized to the modulation frequency.

In order to verify our findings, we fabricated test structures of single rectennas consisting of various noble metals in direct contact with one another, i.e., without a tunnel barrier. Since noble metals do not form a native oxide, no insulating layer is present in these rectennas [see Fig. 4(a)]. All antennas were characterized with respect to their optoelectronic (antenna response under illumination) and electronic (I–V characteristics) properties. We compared the antenna response of several rectennas featuring the same dimensions but different metal combinations [see Fig. 4(a)], and found a linear dependence of the antenna response on the difference in the Seebeck coefficients of the two



(a) (b)

Fig. 4. (a) SEM image of single rectenna consisting of only noble metals without oxide layer. (b) A constant ratio between the open-circuit voltage (VOC) and relative Seebeck coefficients is obtained, and is equal to the average temperature difference between the junctions.

electrodes [see Fig. 4(b)], in excellent agreement with theory:

$$V = (S_{M1} - S_{M2}) \times (T_{\rm hot} - T_{\rm cold})$$

where S_{M1} and S_{M2} are the Seebeck coefficients of the two electrode metals and $T_{\rm hot}$ and $T_{\rm cold}$ are the temperatures of the metals at the hot and the cold junction. The precise Seebeck coefficients are known from previous investigations in which we included thermometer structures close to the individual rectenna structures. Since we did not incorporate thermometer structures into the present antenna array, we infer from Fig. 4(b) that the average temperature difference between the two junctions is the same for all of the tests, and is approximately 5.8 mK. Invoking the rectification mechanism of rectennas with the Seebeck effect also explains why the response of the functioning rectenna sectors is small. Since the difference in the Seebeck coefficients of Au and Ti is relatively small, the induced open-circuit voltage is consequently also smaller than for other possible material combinations with a larger difference of their Seebeck coefficients. Also, the array was not designed to maximize temperature differences across the MIM junctions. If rectennas are built based on the Seebeck effect without the need for a tunnel barrier, the fabrication process is drastically simplified, since the manufacture and implementation of the ultra-thin oxide layers represented one of the key challenges for these devices.

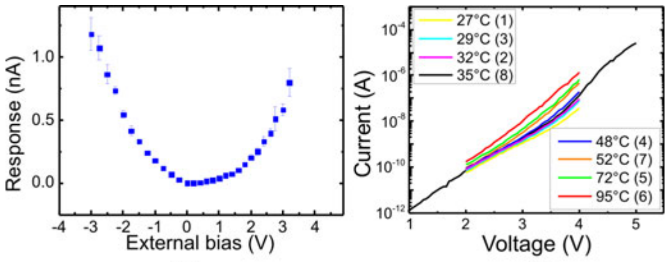
V. ANTENNA RESPONSE IN BIASED RECTENNAS

Believing that the tunneling mechanism is the dominant rectifying mechanism, several groups proposed to bias the rectenna in order to increase the asymmetry of the tunneling currents around the bias voltage, and thus, to increase the rectified current [15], [19] according to the dependence of rectified current on the nonlinearity of the I–V operating point,

$$I_{\rm dc} = \frac{1}{4}\frac{d^2 I}{dV^2}\bigg|_{V=V_{\rm bias}} V_0^2$$

where V_0 is the amplitude of the induced voltage and $V_{\rm bias}$ is the applied voltage.

We also followed this principle and biased ensembles of antennas showing nonlinear I–V characteristics and a lack of response to incident IR radiation at zero bias. When applying an external bias, we obtained an antenna response [see Fig. 5(a)].



(a) (b)

Fig. 5. (a) When externally biasing a sector of the rectenna array that showed no antenna response without an applied bias, an antenna response in the form of a current signal is observed. (b) The temperature-dependent current–voltage characteristics of a MIM diode show that the resistance of the MIM junction decreases with increasing temperature, which is the signature of a bolometer effect.

However, further investigations showed that the response obtained under external bias can also be explained by a standard bolometric effect [47] due to the temperature dependence of the tunnel current. When radiation is incident on the biased rectennas, a resistance change at the MIM junction occurs due to heating. This explanation is supported by our temperature dependent I–V measurements of our MIM junctions [see Fig. 5(b)]. Therefore, the present concept of diode rectification for biased rectennas should be further investigated in light of the contribution due to temperature dependent tunneling.

VI. CONCLUSION

We have reported on the rectification mechanism in IR-sensitive rectennas. Our investigations show that rectification of the terahertz currents induced by the absorbed incident IR radiation is not due to tunneling rectification in the unbiased MIM tunnel junctions, but rather due to the Seebeck effect that results from the temperature gradient in the two different metals of our rectenna structure. We suggest that the response to incident radiation of biased antennas coupled to MIM junctions can also be attributed to thermal effects. Future investigations should give further basis to this statement and show that the ac-signal conversion into dc is more efficient due to thermal effects than to tunnel effects. We further showed a highly efficient method for the fabrication of nanoscale rectenna arrays of nearly one million elements. Our findings offer a new concept that should be implemented into new designs of IR rectenna detectors and solar rectenna arrays for energy harvesting.

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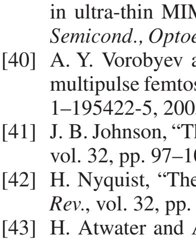

Mario Bareiß was born in Hagen, Germany. He received the Dipl.-Phys. degree in physics in 2009 for his work on InAs quantum dots on InP substrate fabricated with molecular beam epitaxy for the application of a single photon source from the Technische Universität in München (TUM), Munich, Germany, where he is currently working toward the Ph.D. degree in physics at the Institute for Nanoelectronics, TUM.

His current research interests include the fabrication of nanodevices with special focus on the fabrication technology of nanoimprint lithography and nanotransfer printing.

Peter M. Krenz (M'04) received the B.S. degree in electrical engineering from Oklahoma State University, Stillwater, USA, in 2003, the M.S. degree in optics from the University of Central Florida, Orlando, USA, in 2008, and the Ph.D. degree in optics from the College of Optics and Photonics, University of Central Florida, Orlando, in 2010.

He is currently a Post-Doctoral Researcher with the Center for Nano Science and Technology, University of Notre Dame, Notre Dame, IN, USA. His current research interests include simulation, fabrication, and characterization of uncooled antenna-coupled infrared detectors and infrared transmission lines.

Gergo P. Szakmany received the Diploma in electrical and computer engineering from Pazmany Peter Catholic University, Budapest, Hungary, in 2007, and the M.S. degree in electrical engineering in 2011 from the University of Notre Dame (UND), Notre Dame, IN, USA, where he is currently working toward the Ph.D. degree in electrical engineering, focusing on antenna-coupled infrared detectors.

His current research interests include submicron device fabrication and characterization.

Badri N. Tiwari was born in Kanpur, India. He received his Bachelor of Technology (B.Tech.) degree in Electronics and Communication Engineering from Institute of Technology, Banaras Hindu University (IT-BHU), Varanasi, India, in 2003, and the Master of Science (M.S.) degree in electrical engineering in 2007 from UND, where he is currently working toward the Ph.D. degree.

For two years (2003–2005), he was in Defense Avionics Research Establishment (DARE), Bangalore, India, as a Radio Frequency (RF) Scientist. In 2005, he joined Prof. Wolfgang Porod's research group to work on the design, fabrication, and characterization of antenna detection based infrared sensors at University of Notre Dame (UND). His current research interests include metal–oxide–metal diode and thermoelectric effect based sensors, high-frequency antenna design and simulation, thermal modeling of passives, nanofabrication, and electrical and optical characterization.

Daniel Kälblein was born in Heidelberg, Germany. He received the Diploma in physics from the Technische Hochschule Karlsruhe, Karlsruhe, Germany, in 2007, and the Ph.D. degree in physics from the École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, in 2011.

He is currently a Scientist with the Organic Electronics Group, Max Planck Institute for Solid State Research, Stuttgart, Germany. His current research interests include field-effect transistors and circuits based on inorganic semiconducting nanowires and carbon nanotubes.

Alexei O. Orlov received the M.S. degree in physics from Moscow State University, Moscow, Russia, in 1983, and the Ph.D. degree from the Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow, in 1990.

He is currently a Research Professor with the University of Notre Dame (UND), Notre Dame, IN, USA. From 1983 to 1993, he was with the Institute of Radio Engineering and Electronics, Russian Academy of Sciences. He has conducted research on mesoscopic and quantum ballistic effects in electron transport of GaAs field-effect transistors. He was a Visiting Fellow with the University of Exeter, Exeter, U.K., in 1993, and joined the Department of Electrical Engineering, UND, in 1994. He has authored or coauthored more than 70 journal publications. His current research interests include the experimental studies of mesoscopic, single-electron and molecular electronic devices and sensors, nanomagnetics, and quantum-dot cellular automata.

Gary H. Bernstein (F'06) received the B.S.E.E. (with honors) from the University of Connecticut, Storrs, USA, in 1979, the M.S.E.E. from Purdue University, West Lafayette, IN, USA, in 1981, and the Ph.D. degree in electrical engineering from Arizona State University, Tempe, USA, in 1987.

He joined the University of Notre Dame, Notre Dame, IN, in 1988, and was the founding Director of the Notre Dame Nanoelectronics Facility from 1989 to 1998. He has authored or coauthored more than 200 publications in the areas of electron beam lithography, quantum electronics, high-speed integrated circuits, electromigration, MEMS, and electronics packaging.

Dr. Bernstein received an NSF White House Presidential Faculty Fellowship in 1992, was promoted to rank of Professor in 1998, and served as the Associate Chairman of his Department from 1999 to 2006. He was first author of the IEEE TRANSACTIONS ON ADVANCED PACKAGING Best Paper of the Year in 2007.

Giuseppe Scarpa received the Graduate degree in electrical engineering from the University of Rome "Tor Vergata," Rome, Italy, in 1998, and the Ph.D. degree from the Walter Schottky Institute, Technical University of Munich, Garching, Germany, in 2003.

He was involved in research on design and fabrication of quantum cascade lasers. He is currently with the Institute for Nanoelectronics, where he successfully completed his Habilitation in the fields of nanoelectronics and molecular electronics in March 2009. His current research interests include fabrication of a variety of nanostructures (such organic devices and nanomagnets) and the development of various nanofabrication technologies based on nanoimprint lithography.

Bernhard Fabel was born in Teheran, Iran. He received the Diploma (Dipl.-Ing.) in electrical engineering in 2004 and the Dr.-Ing. degree in 2010 from the Technical University of Munich, Munich, Germany.

He is currently with the Institute of Nanoelectronics, Technical University of Munich, as a Research Assistant. His current research interests include printable nanosclaled electronics and organic devices.

Ute Zschieschang received the Diplomingenieur degree in mechanical engineering from Mittweida University of Applied Sciences, Mittweida, Germany, in 2000, and the Ph.D. degree in chemistry from the Technical University Bergakademie Freiberg, Freiberg, Germany, in 2006.

Since 2005, she has been a scientist in the Organic Electronics Group, Max Planck Institute for Solid State Research, Stuttgart, Germany. Her current research interests include high-performance conjugated semiconductors, self-assembled monolayers, and micropatterning techniques for organic devices and circuits.

Hagen Klauk (S'97–M'99) received the Diplomingenieur degree in electrical engineering from Chemnitz University of Technology, Chemnitz, Germany, in 1995, and the Ph.D. degree in electrical engineering from the Pennsylvania State University (Penn State), University Park, USA, in 1999.

From 1999 to 2000, he was a Postdoctoral Researcher at the Center for Thin Film Devices at Penn State. In 2000, he joined Infineon Technologies, Erlangen, Germany. Since 2005, he has been head of the Organic Electronics Group, Max Planck Institute for Solid State Research, Stuttgart, Germany. His current research interests include flexible transistors and circuits based on organic semiconductors, carbon nanotubes, and inorganic semiconductor nanowires.

Wolfgang Porod (F'01) received the Diploma (M.S.) and the Ph.D. degrees from the University of Graz, Graz, Austria, in 1979 and 1981, respectively.

After appointments as a postdoctoral fellow at Colorado State University and as a Senior Research Analyst at Arizona State University, he joined the University of Notre Dame in 1986 as an Associate Professor, where he is currently Frank M. Freimann Professor of Electrical Engineering and the Director of Notre Dame's Center for Nano Science and Technology. His current research interests include nanoelectronics, with an emphasis on new circuit concepts for novel devices. He has authored or coauthored some 300 publications and presentations.

Dr. Porod was the Vice President for publications for the IEEE Nanotechnology Council (2002–2003), and he was appointed an Associate Editor for the IEEE TRANSACTIONS ON NANOTECHNOLOGY (2001–2005). He has been active on several committees, in organizing Special Sessions and Tutorials, and as a speaker in IEEE Distinguished Lecturer Programs.

Paolo Lugli (F'10) received the Laurea degree in physics from the University of Modena, Modena, Italy, in 1979, and the M.Sc. and Ph.D. degrees in electrical engineering from Colorado State University, Fort Collins, USA, in 1982 and 1985, respectively.

In 1993, he was appointed as a Full Professor of optoelectronics with the Universita di Roma "Tor Vergata," Rome, Italy. Since 2002, he has been with the Technische Universität München (TUM), Munich, Germany, as the Head of the newly created Institute for Nanoelectronics, TUM. His current interests include modeling and simulation of nanostructures, as well as the realization and characterization of organic devices.