Schottky Barrier Contact-Based RF MEMS Switch

Brandon Pillans, Member, IEEE, Frank Morris, Prem Chahal, Member, IEEE, Gary Frazier, and Jeong-Bong Lee, Senior Member, IEEE

Abstract—This paper presents the design, fabrication, and measurement results for a novel Schottky barrier contact-based radio frequency (RF) microelectromechanical systems (MEMS) switch. This Schottky barrier contact allows one not only to operate the RF MEMS switch in a traditional capacitive mode when it is reverse biased but also conduct current in a forward biased state. Forward biasing the switch recombines trapped charges, thus extending the lifetime of the switch. This paper intimately combines MEMS processing with solid-state electronics to produce a truly unique RF device.

Index Terms—Microelectromechanical devices, microwave switches, reliability, Schottky barriers, semiconductor materials.

I. INTRODUCTION

MICROELECTROMECHANICAL systems (MEMS) have permeated many commercial and defense systems through the use of accelerometers, ink-jet printer nozzles, and microdisplay devices to name a few [1]. By shrinking traditional components to the microscale, advantages to cost, power, and performance can be realized. However, because these devices are all mechanical in nature and the forces involved are small, reliability becomes a key concern in how quickly the technology can be implemented. For the devices previously mentioned, the reliability has been extensively studied and improved upon such that these components can be found in even the most demanding and critical applications such as automobile airbag deployment sensors. For newer types of MEMS devices such as radio frequency (RF) switches, the reliability is still in question and must be improved and demonstrated for systems to take advantage of the superior performance.

RF MEMS switches offer a high-performance low-power low-cost alternative to traditional diode switches [2], but improving the reliability of these devices remains of critical importance in accelerating the widespread adoption of this technology. This paper expands upon the brief version presented at the MEMS 2007 conference [3].

Dielectric stiction is the primary failure mode in capacitive switches [4] and the failure mode of interest for this paper. High electrostatic fields across the thin dielectric cause charge to tunnel into the dielectric, where it remains trapped for an extended amount of time due to long recombination times. Over time, these charges accumulate and can reach a point at which the voltage present in the dielectric is enough to hold the switch down or screen the applied voltage; thus, the switch does not actuate. If the switch is actuated and held down, it will not release until sufficient time has allowed the charges to recombine. Charge trapping such as this has been investigated for more than 20 years, because understanding this trapping is essential to metal–oxide–semiconductor (MOS) transistors. RF MEMS capacitive switches have three trapping areas that can cause failures: the surface traps on top of the dielectric, the bulk traps inside the dielectric, and the interface traps between the metal and dielectric layer, as shown in Fig. 1.

This trapping phenomenon has been well documented in [5]–[9] for MOS devices. In general, the charging of the dielectrics is due to the application of some type of stress such as electrical field, thermal, mechanical, or ionizing stresses. The electrons are trapped at lower electric fields (2–5 MV/cm) and detrapped at high fields, while the positive charges are typically trapped at high fields (7–10 MV/cm) [6]. The surfaces and interfaces are the areas where defects are concentrated and charges will be preferentially trapped [7]–[9].

As an example, the Raytheon RF MEMS switch uses a 150-nm-thick Si$_3$N$_4$ dielectric and is actuated with 40 V [4]. Just before the switch is actuated, the 40-V field is divided across the $4_{\mu}$m air gap and dielectric. After the switch makes contact with the dielectric, the full 40-V field is across the 150-nm Si$_3$N$_4$, creating a 2.7-MV/cm field in the dielectric layer. Under this high field strength, it is possible for the charges to tunnel into the dielectric using a Frenkel–Poole emission [7]–[11] or through another set of mechanisms [12]. Once inside these trap states, the charge can be transported using a conduction model [11] and might take seconds to days to recombine [13].

One obvious solution to this problem is to reduce the actuation voltage of the switch to reduce the electric field across the
dielectric [10]. As the field is reduced, the charging improves exponentially, thus extending the lifetime of the switch. The consequence of this approach is that, as the actuation voltage decreases, the restoring force of the switch also decreases, meaning that there is less force to pull the switch back up to the unactuated state. There is a trade to be made on how fast the switch charges up and how much restoring force is needed for long lifetime. For this reason, most of the RF MEMS switch designers prefer an actuation voltage of 25–35 V [4]. These voltages, however, still exhibit a high electrostatic field that introduces charges into the dielectric.

Another potential solution is to reduce the bias voltage on the switch once it has snapped down to the dielectric, because only a fraction of the actuation voltage is needed to hold the switch down. By stepping the voltage from 40 to 10 V after the switch is actuated, as shown in Fig. 2(a), the electrostatic field is reduced to 0.67 MV/cm. Although this method increases the lifetime of the switch dramatically [4], the small amount of time when the switch is actuated and the full actuation voltage is still applied (before the step) allows the dielectric to charge. Another method is to reverse the polarity of the electrostatic field across the dielectric to pull the trapped charges out, as shown in Fig. 2(b). Because both positive and negative voltages will actuate the switch, flipping the polarity should help to balance the charge injection to create a neutral condition. Although this method helps, its ultimate effectiveness is limited by the fact that the rate of charge injection is not equal in the positive and negative directions [4] and that, over time, the charge will accumulate in one direction or the other and cause a failure. Because each switch has slightly different characteristics due to manufacturing, an individual switch can be fine tuned to show no charging, but tuning many thousands of switches simultaneously is too difficult to be practical.

Another option is to reduce or eliminate the actual area that the metal membrane and dielectric make contact. By building an RF MEMS varactor [14], the dielectric/membrane interface is completely eliminated, and no dielectric charging can occur. However, the price paid is that the capacitance ratio for the device is less than 4:1 versus the 100:1 ratio for the standard Raytheon switch [2]. Depending on the application and the frequency, this reduction in RF performance can be very significant and is often not used for that reason. Another way to accomplish the same idea is to not totally eliminate the dielectric contact but limit it [15], as shown in Fig. 3. In this configuration, small standoff posts are patterned to keep the membrane from shorting to the electrode and provide some higher capacitance ratios. The ratio can vary anywhere from 100:1 to 5:1, depending on the number of posts, and is essentially a trade with RF performance and reliability.

The only solution that attacks dielectric charging at its source is to alter the dielectric material. For instance, it is well known that plasma enhanced chemical vapor deposition (PECVD) silicon dioxide has a much lower trap density than PECVD silicon nitride [11]. By simply changing dielectrics, dielectric charging can be reduced but not eliminated. The penalty is that the dielectric constant of SiO$_2$ is almost twice as low as Si$_3$N$_4$, causing a reduction in the capacitance ratio, and the switch will still charge eventually.

One way to attack the problem is to reduce the recombination time of the charges in the dielectric by depositing a leaky dielectric [16]–[18] such as silicon-rich silicon nitride that allows an appreciable current flow through the dielectric. By increasing the conductivity of the dielectric, the trapped charges can recombine quickly and not cause dielectric stiction. The problem with this approach is that the dc current flow of the switch is now not negligible and one of the primary benefits of RF MEMS switches is that they require almost no dc power to operate. The ideal solution would be to deposit a dielectric that is an excellent insulator with no trap states. The problem with this approach is that all materials will exhibit some type of trap states. Moreover, the processes required to deposit low trap state materials, such as jet vapor deposition [19], are typically performed at high temperatures that are incompatible with RF MEMS devices in addition to being cost prohibitive.

The ideal RF MEMS switch would be able to change the conductivity of the dielectric at will. This would allow charges to recombine quickly only when it was necessary, thus conserving power consumption. A p-n junction performs like a good capacitor when it is completely depleted under reverse bias and like a low resistance short when forward biased. By building a Schottky diode with membrane metal and a semiconductor in place of the conventional dielectric, the switch should be able to operate as a typical capacitive RF MEMS switch in reverse bias, and once the charges start to accumulate, the switch can be forward biased at will to quickly and effectively recombine any trapped charges. This will be the focus of the work presented in this paper.

**III. DESIGN**

The RF MEMS Schottky switch design is based on Raytheon’s fixed-fixed beam capacitive switch [2] that has been very well characterized and is shown in Fig. 4. In both switches, the dielectric contact area is 118 $\times$ 130 $\mu$m. In this paper, the switch structure is primarily the same as the Raytheon-style switch except that the device is built on an undoped InP...
substrate, the gold electrode is replaced by $n^{++}$ InGaAs, and the dielectric used is epitaxial InAlAs (1 $\mu$m thick). These layers were grown using Molecular Beam Epitaxy (MBE) on the InP substrate. The total cross section is shown in Fig. 5. InAlAs was chosen as the Schottky material because of the relatively high bandgap and ease of processing. Because InAlAs needs to be epitaxially grown, the traditional gold electrode had to be replaced. A degenerately doped InGaAs layer was chosen because of its lattice compatibility with InAlAs.

The Schottky MEMS switch was designed to have an actuation voltage of 24 V, which is critical in keeping the maximum voltage low enough so as to not break down the reverse-biased dielectric. The rough dimensions of the beam are 320 $\mu$m long by 118 $\mu$m wide at the dielectric contact area. The modeled on-capacitance was 0.5 pF, and the modeled off-capacitance was 40 fF.

When the aluminum membrane is actuated, a Schottky barrier forms at the membrane/dielectric interface. The switch bias waveform shown in Fig. 6 is used to actuate the switch and hold it down as needed, and just before it is released, a quick forward bias pulse recombines any trapped charge, essentially resetting the switch and improving the reliability.

### IV. Results

The Schottky barrier RF MEMS switch was successfully fabricated, as shown in Fig. 7. The first characterization step was to measure the $I$–$V$ characteristics of the switch in the actuated position and look for a diode response to prove that the concept works. Because the semiconductor parameter analyzer (SPA; HP 4155B) used to measure the $I$–$V$ characteristics collects data very slowly, the switch would not remain in the actuated position as the voltage is scanned from $-30$ to $+6$ V. Fig. 8 shows the $I$–$V$ switch response as the voltage is slowly swept from zero to $-30$ V and back to zero. RF MEMS switches require the pull-down voltage ($V_p$) to actuate the membrane, and then, a much lower voltage known as the hold voltage ($V_h$) is needed to hold the switch down. This curve in Fig. 8 shows the unique $I$–$V$ profile of a Schottky diode that is made and broken by the mechanical membrane contacting and releasing from the Schottky dielectric. When the switch is unactuated, the current is essentially zero. As the membrane is pulled down ($-22$ V) to the InAlAs, the current behaves like a reverse-biased Schottky diode. As the voltage is ramped back
to 0 V, the membrane releases (−13 V), and the current drops immediately to zero.

To show the full functionality of the device, the \( I-V \) measurements of both the reverse and forward bias states are needed. Because the SPA cannot collect the forward bias data before the switch releases, a mechanical probe was used to force the switch into the actuated position regardless of voltage. The \( I-V \) characteristics of this device in the actuated state as the SPA is swept from −35 to +6 V are shown in Fig. 9. It is easy to see that the switch is indeed operating as Schottky diode when the switch is actuated. The reverse breakdown region of the diode is seen at −35 V, the reverse saturation current measures around 500 nA, and the diode “turn-on” voltage occurs at 5 V.

One important characteristic to note is that the measured turn-on voltage was extremely high. Typically, a Schottky diode turn-on voltage is much less than 1 V, and this device measured 5 V. To check the basic Schottky diode characteristics, another device was fabricated at the same time that was built permanently in the actuated position. This device is known as a “faux” switch because it represents a perfectly actuated switch fabricated in the “down” position with the exact same dimensions as the real switch. The \( I-V \) characteristics of this faux switch are shown in Fig. 10. This curve shows a much more typical Schottky response with a reverse breakdown voltage of −25, saturation current around 100 nA, and a diode turn-on voltage of ~0.25V. By taking \( I-V \) data across temperature and extracting the results, the InAlAs barrier height was found to be 0.65 eV, which compares well to Salem [20], and the effective Richardson constant was found to be 6.7 A cm\(^{-2}\)K\(^{-2}\), which agrees well with Pilkington [21].

The turn-on voltage difference between the Schottky switch and the faux device can be explained through the oxide formation on the aluminum membrane. While a certain amount of native oxide always exists on aluminum, the oxygen plasma used to etch the sacrificial photoresist under the membrane greatly increased the Al\(_2\)O\(_3\) thickness. Rough calculations show around 30 Å of interfacial oxide between the aluminum and the InAlAs. This interfacial oxide (shown in Fig. 11) essentially acts like a voltage divider that increases the Schottky diode turn-on voltage.

The following discussion briefly touches on the different charge transport mechanisms that may exist in this system. To understand the basic mechanism behind the presence of an interfacial oxide layer, Sharma [20] explains that its presence results in three things: Because of voltage drop across this layer, the zero bias barrier height is lower than it should be; because the electrons have to tunnel through the oxide, the diode current
Fig. 11. Illustration of interfacial oxide layer in the Schottky MEMS switch.

is reduced below the value predicted in the ideal Schottky diode equations; and because a part of the applied voltage appears across the oxide, the barrier height becomes a function of the applied voltage. The barrier height can now be considered as a function of the applied bias shown as \[ \phi_B = \phi + \beta q V \] (1)

where \( \phi_{B0} \) is the zero bias barrier height, \( V \) is a positive number for forward bias, and \( \beta \) is positive and is defined as the change in barrier height over voltage by \[ \beta = \frac{\partial \phi_B}{\partial V}. \] (2)

By plugging (2) into the ideal diode equation, a new model for the forward bias current that includes an interfacial oxide is shown as

\[
I = I_o \left[ \exp \left( \frac{q(1 - \beta)V}{kT} \right) - 1 \right] \tag{3}
\]

where \( I_o = S A^* T^2 \exp(-q \phi_B/kT) \) with \( S \) as the diode cross-sectional area and \( A^* \) as the modified Richardson constant.

The net result of the interfacial oxide is that only a small fraction of the applied voltage is seen at the diode; therefore, the measured switch current is much smaller for a given bias voltage than the corresponding faux device. In addition, when a strong forward bias voltage is used to drive higher currents, the interfacial oxide eventually breaks down, and the entire applied bias is across the diode. This very high voltage drives massive current and easily exceeds the maximum current density of the aluminum membrane. The result is a catastrophic breakdown of the device. It is therefore not advisable to force high currents through the switch by increasing the bias voltage significantly.

To fully understand how the oxide is affecting the Schottky MEMS switch, several current conduction models through the oxide are tested to see how each one fits the measured data. These plots are shown in Fig. 12. The most likely current conduction mode through the oxide is through direct tunneling using a Fowler–Nordheim [11] charge transport model described as

\[
J \sim \varepsilon^2 \exp \left[ -\frac{4\sqrt{2m^* (q\phi_B)^{3/2}}}{3q\varepsilon kT} \right] \tag{4}
\]

where \( \varepsilon \) is the electric field strength, and \( m^* \) is the effective mass. This curve is shown in Fig. 12 and does not show very good agreement with the measured data. A Frenkel–Poole model [11] is also tested and is shown in Fig. 12. This model is described as

\[
J \sim \varepsilon \exp \left[ -\frac{q(\phi_B - \sqrt{q\varepsilon/\pi \varepsilon_i kT}}{kT} \right] \tag{5}
\]

where \( \varepsilon_i \) is the oxide permittivity. By adjusting the oxide thickness to 38 Å, the Frenkel–Poole model fits the data well. Because the chance of a charge going over the potential barrier as the Frenkel–Poole model suggests is very small considering the wide bandgap nature of \( \text{Al}_2\text{O}_3 \), the charges are more likely tunneling into a trap state in the oxide and, from there, following a Frenkel–Poole transport mechanism into the diode. Another theory is that there are ample trap states and ions inside the oxide, which are being transported because of the low-quality oxide. Also shown in Fig. 12 is the interfacial oxide Schottky model presented in (3) with a fitted \( \beta = 0.984 \) that shows excellent correlation with the measured data. Fig. 13 shows the modeled and measured data for both the faux device and the Schottky MEMS switch. Future iterations of this device should try and reduce or eliminate this native oxide layer by using a nonoxidizing metal such as gold instead of aluminum.

V. RF PERFORMANCE

A complete analysis of the RF performance of the switch is presented in [21], but a summary is presented as follows. A comparison of the modeled and measured $S$-parameters for the switch is shown in Fig. 14. Because the heavily doped InGaAs is used as the switch electrode instead of the traditional gold, the insertion loss is higher than the baseline Raytheon MEMS switch described in [2]. At 35 GHz, the insertion loss is 1.1 dB in the unactuated state, and the isolation is 14 dB when the switch is actuated. As shown in Fig. 14, these numbers compare well with the simulated $S$-parameters.

One of the more important characteristics of an RF MEMS switch is the fact that there are no visible intermodulation products (IPs) because only metals are used to build the devices. Using the Schottky RF MEMS switch, a nonlinear junction is introduced that could potentially affect the linearity of the device. A full characterization of the second order IP (IP2) is reported in [21]; however, a summary of that testing is shown in Fig. 15. In the unactuated position, there is no Schottky contact and, thus, no nonlinearities; therefore, the Schottky switch looks identical to the baseline Raytheon MEMS switch. When the switch is actuated, the Schottky contact is made, but because the switch is so heavily reversed bias and the depletion region covers essentially the entire thickness of the InAlAs dielectric, the switch exhibits an IP2 of 81 dBm, which is still better than traditional switching technologies (field-effect transistor; p-i-n).

VI. LIFETIME TESTING

The primary reason for building this Schottky contact RF MEMS switch is to improve the lifetime over the baseline capacitive switch design. Life testing is a very slow process because of the relatively slow switching speed of these devices. Even at a switching rate of 10 kHz, it would take over three years to reach a goal of one trillion cycles. Even so, life testing has been ongoing with these devices and currently shows over ten billion actuations without a failure. As a way to quickly assess the reliability of MEMS switches, an accelerated life test is employed that can gauge the relative lifetime of two switches. By actuating the switch with a high voltage, dielectric charging is enhanced. By increasing the temperature, the restoring force of the membrane is reduced due to the coefficient of thermal expansion mismatch between the Aluminum membrane and the substrate. Both of these conditions will accelerate a failure. The amount of time it takes for a switch to fully release after the voltage has been removed is known as the switch release time ($t_r$). Initially, the release time for all switches correlates exactly with the bias voltage returning to zero. As dielectric charging occurs during the lifetime of the switch, experience shows that the release time slowly increases. Eventually, this time becomes so long that the switch is considered “stuck down” or failed. By tracking the release time of the switch versus a set number of cycles, one can see an early indicator of relative failure between two switches. Although these data are difficult to extrapolate to a final reliability number, their use as a relative measurement is acceptable.

Fig. 16 shows a plot of release time for a Schottky MEMS switch and a baseline switch after they both underwent one million actuations. The gray triangle trace shows the bias of the baseline switch, while the black diamond trace shows the Schottky MEMS switch bias. One can see that both bias waveforms start and end at the same time, but the Schottky bias voltage flips polarity to a positive 3 V of forward bias at the end of the cycle to recombine trapped charges in the dielectric. The
gray-circle (baseline) and black-square (Schottky) curves show the relative switch position as a function of the bias voltage. In this setup, a laser is used to illuminate the switch membrane, and a photodetector is used to measure the intensity of the reflected laser. Photograph and diagram of this test setup are shown in Fig. 17.

As shown in Fig. 16, the Schottky MEMS switch shows a 35% improvement in the release time of the switch, indicating that it exhibits increased reliability compared to a baseline RF MEMS switch. Because both of these switches started with the same release time initially, these data indicate that the Schottky switch is charging slower than the baseline switch. The exact amount of improvement is still unknown, but the trend indicates a superior switch with regard to reliability.

VII. Conclusion

The work presented in this paper on a Schottky barrier contact RF MEMS switch sets the stage for a new class of solid-state devices integrated with MEMS technology—not only in building the devices on the same substrate but also actually making the MEMS structures part of the solid-state device operation. This paper demonstrated that a movable MEMS membrane can be used to form a Schottky diode and is a first in any published literature. This concept shows a unique integration of mechanical systems with high-speed electronics that could be used in areas outside of both RF systems and MEMS. A summary of the measured versus modeled switch characteristics is shown in Table I.

TABLE I
SUMMARY OF SCHOTTKY RF MEMS SWITCH CHARACTERISTICS

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Modeled</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuation Voltage</td>
<td>23.8 V</td>
<td>22 V</td>
</tr>
<tr>
<td>Hold Voltage</td>
<td>2.3 V</td>
<td>3 V</td>
</tr>
<tr>
<td>Insertion Loss @ 35 GHz</td>
<td>-0.97 dB</td>
<td>-1.1 dB</td>
</tr>
<tr>
<td>Isolation @ 35 GHz</td>
<td>-13.8 dB</td>
<td>-14 dB</td>
</tr>
<tr>
<td>Forward Bias Current @ 1 V</td>
<td>0.65 nA</td>
<td>0.35 nA</td>
</tr>
<tr>
<td>@ 2 V</td>
<td>1.67 nA</td>
<td>1.12 nA</td>
</tr>
<tr>
<td>Reverse Bias Current @ -20 V</td>
<td>-2.2 nA</td>
<td>-1.92 nA</td>
</tr>
<tr>
<td>@ -30 V</td>
<td>-2.9 nA</td>
<td>-3.9 nA</td>
</tr>
<tr>
<td>Linearity IP2</td>
<td>81.3 dBm</td>
<td>81 dBm</td>
</tr>
</tbody>
</table>

Fig. 17. Test setup for accelerated life testing.

REFERENCES

Brandon Pillans (M’98) received the B.S. and M.S. degrees in electrical engineering from Texas A&M University, College Station, in 1996 and 1998, respectively, and the Ph.D. degree from The University of Texas at Dallas, Richardson, in 2006. He was with Raytheon Systems Company in 1998, performing RF microelectromechanical system (MEMS) switch research and development. While in the RF MEMS group, he performed many RF MEMS microwave monolithic integrated circuit designs such as a Ka-band phase shifter that has measured world record performance in addition to tunable bandpass and bandstop filters and tunable impedance matching networks. He has also worked extensively on increasing the reliability of the capacitive RF MEMS switch, resulting in six orders of magnitude increase in switch lifetime over that period. He has written over 16 published articles on MEMS technology and is the holder of three RF MEMS patents. He is currently the Technical Lead of the RF MEMS Group, Raytheon Company, Dallas, TX. He is also with The University of Texas at Dallas.

Frank Morris received the B.S., M.S., and Ph.D. degrees from North Carolina State University, Raleigh, in 1962, 1964, and 1968, respectively. He is an Engineering Fellow with Raytheon Company, Dallas, TX, and has over 30 years of silicon and/or III–V process experience in research and development. He is the holder of several patents in these areas. He is currently responsible for Raytheon’s RF microelectromechanical system (MEMS) process development, where he is fabricating MEMS phase shifters and filters.

Prem Chahal (M’00) received the M.S. and B.S. degrees in electrical and computer engineering from Iowa State University, Ames, and the Ph.D. degree in electrical engineering from Georgia Institute of Technology, Atlanta, in 1999. He is currently with Abbott Laboratories, Abbott Park, IL, developing sensors and systems for drug discovery applications. From 1999 to 2006, he was with the Nanoelectronics Group, Raytheon Company, Dallas, TX, where he carried out research in the areas of terahertz circuits and systems, microwave photonics, infrared sensors, and packaging for RF microelectromechanical systems and microwave monolithic integrated circuits.

Gary Frazier received the B.S. degree in electrical engineering from the University of Maryland, College Park, in 1975, and the Ph.D. degree in physics from The University of Texas at Dallas, Richardson, in 1983. In previous work in nanoelectronics, he led numerous world’s first demonstrations of quantum technology, including quantum dot transistors; quantum dot logic elements; resonant tunneling transistors and logic circuits; microwave analog-to-digital converters; and submillimeter-wave radio-frequency quantum tunneling detectors and sources. He is the holder of more than 50 patents on resonant tunneling electronics, neural networks, computer architecture, fiber optics, submillimeter-wave communications, digital radar, nanomechanical electronics, and advanced optical display technology and systems. He is a Senior Engineering Fellow with the Advanced Products Center (APC), Raytheon Company, Dallas, TX, where he is a member of the Emerging Technologies Group, APC Engineering, which is currently developing microelectromechanical devices and advanced display technologies.

Jeong-Bong Lee (S’92–M’98–SM’08) received the B.S. degree in electronics engineering from Hanyang University, Seoul, Korea, in 1986, and the M.S. and Ph.D. degrees in electrical engineering from Georgia Institute of Technology, Atlanta, in 1993 and 1997, respectively. He is currently a Tenured Associate Professor with the Department of Electrical Engineering, The University of Texas at Dallas, Richardson. He has been serving as a member of the external review panel for the Microsystems Division, Sandia National Laboratories, since 2007. His current research interests include RF and biomedical applications of microelectromechanical systems and nanophotonics. Dr. Lee received a National Science Foundation CAREER Award in 2001.