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Measurement of Plasma Density Generated by a Semiconductor Bridge: Related Input Energy and Electrode Material

Jongdae Kim and K. C. Jungling

CONTENTS

ABSTRACT

The plasma densities generated from a semiconductor bridge (SCB) device employing a capacitor discharge firing set have been measured by a novel diagnostic technique employing a microwave resonator probe. The spatial resolution of the probe is comparable to the separation between the two wires of the transmission lines ($\approx$ 3 mm). This method is superior to Langmuir probes in this application because Langmuir probe measurements are affected by sheath effects, small bridge area, and unknown fraction of multiple ions. Measured electron densities are related to the land material and input energy. Although electron densities in the plasma generated by aluminum or tungsten-land SCB devices show a general tendency to increase steadily with power, at the higher energies, the electron densities generated from tungsten-land SCB devices are found to remain constant.

I. INTRODUCTION

A semiconductor bridge (SCB) is a small electronic device [1], designed to replace a hot wire in setting off chemical explosives because it functions in a few tens of microseconds and operates at one-tenth the input energy of conventional hot-wire devices [2]. Even though the SCB device ignites at input energies approximately one-tenth that of bridge wire devices, tests have shown the SCB devices to be relatively RF insensitive and safe as compared to a conventional bridgewire. Therefore, these devices have a wide range of uses in such areas as automotive airbags, mining, rocket ignition, and various firing system.

The SCB device performs the function of an electro-explosive igniter when subjected to an appropriate electrical energy pulse. Since the input energy generates a plasma from the bridge and the lands [3], [4], it is important to know how efficient this process is as a function of bridge and electrode material. In addition, information on plasma constituents, identification of emitting species [5], plasma temperature [5], and plasma density distribution can yield a better understanding of the SCB discharge behavior. There is little data on plasma electron density of SCB devices as a function of input energies and land materials in the literature. The purpose of this paper is to report measurements of the plasma electron densities of the SCB devices in vacuum related to the land material and input energy. To consider the effects of the electrode material, tungsten (W) is used in addition to aluminum (Al).

II. MEASUREMENT PRINCIPAL AND PROBE DESIGN

A typical SCB device consists of an “H” shaped thin Silicon-On-Sapphire (SOS) film and two metal lands for electrical contacts lying over the outer legs of the “H” shaped film. Figure 1 shows one of these SCB structures, in which the SOS film has been highly doped ($\sim 10^{20}$ cm^{-3}) with phosphorous impurities and the metal lands are formed by deposition of an aluminum or a tungsten layer onto the n^+ silicon film. The SCB geometry can be described by its length (L), width (W), and thickness (th) to yield the 1.0 Ω static resistance. Static resistance of a diffused semiconductor film is calculated using $R = L/\sigma th W$ where σ represents the electrical conductivity of the doped silicon film. Application of a voltage pulse across the SCB device results in a melting and vaporization. When the bridge is completely vaporized, the vapor provides a dense gaseous conductor spanning the lands of the device. This dense gaseous material can be resistively heated to produce a plasma.

In this section, a microwave resonator probe technique [6]-[9] is described which is both simple and suited for measuring time-varying plasma density produced by an SCB device. This simple diagnostic tool is based on a microwave technique for measuring the cold plasma permittivity and is largely independent

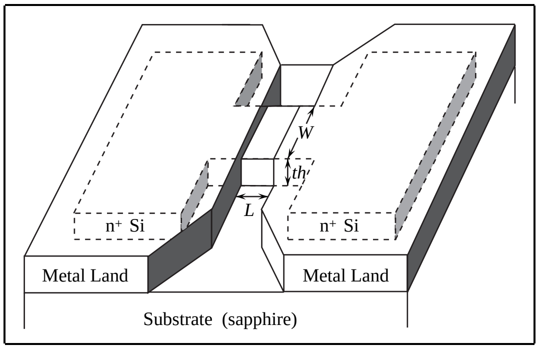

Fig. 1. Schematic view of a typical SOS-SCB device. The bridge is the heavily doped silicon area between the two metal lands.

of sheath and thermal effects. Unlike the more familiar cavity resonance shift method, it is suited for localized density measurements. Using this technique, very precise time dependent measurements of the plasma electron density generated by the SCB device can be obtained without requiring knowledge of ion mass or electron temperature.

Laboratory-produced plasmas show resonant behavior when subjected to electromagnetic waves in the frequency range of microwaves. Among these resonances, the one at the plasma frequency ω_p plays an especially important role since it allows the determination of the plasma electron density n_e through

$$\omega^2{}_p = \frac{n_e e^2}{\varepsilon_0 m_e} \tag{1}$$

where e and m_e are the electron charge and mass, and ε_0 is the vacuum permittivity. The plasma dielectric constant is given by

$$\varepsilon_r = 1 - \left(\frac{\omega_p}{\omega}\right)^2 . \tag{2}$$

The resonant behavior markedly alters the microwave propagation through a plasma. When an open, parallel-wire transmission line is immersed in a uniform medium of dielectric constant ε_r, the propagation constant is given by

$$k = \frac{\omega}{c}\sqrt{\varepsilon_r} \tag{3}$$

where c is the velocity of light in vacuum. The resonator structure consists of a quarter-wavelength ($kl = \pi/2$) section of a parallel-wire transmission line, one end shorted and the other end open. It exhibits a resonance at, with the help of (3),

$$\omega_{res} = \frac{\pi c}{2l\sqrt{\varepsilon_r}} \tag{4}$$

where l is the length of the resonant structure. If the dielectric medium is a field-free plasma with a dielectric constant given as (2), the resonance frequency of a quarter-wavelength of transmission line ω_{res} is increased from its value in vacuum ω_{ores} to

$$\omega^2{}_{res} = \omega^2{}_{ores} + \omega^2{}_p . \tag{5}$$

Therefore, a measurement of the probe resonant frequencies in vacuum and in a plasma allows one to quickly obtain the plasma frequency or electron density (n_e) through

$$n_e = \frac{\omega^2{}_p \varepsilon_0 m_e}{e^2} . \tag{6}$$

The actual construction of the microwave resonator probe designed for these experiments is shown in Fig. 2. The resonant structure is a parallel-wire transmission line made from a pure silver wire with a diameter of 0.05 mm. The 99.9 % pure silver wire (Johnson Matthey Mater. Tech., U.K.) with a small diameter was used to make a parallel-wire trans-

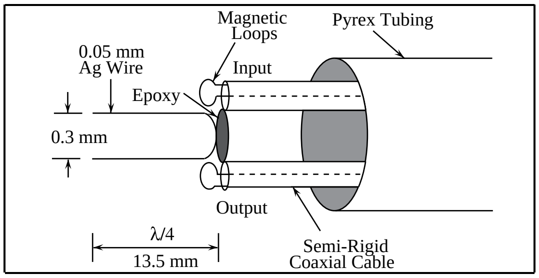

Fig. 2. Schematic view of the microwave resonator probe.

mission line since it has a high electrical conductivity and results in a high Q device. The wire thickness should be kept as small as possible so as to minimize surface losses and associated density gradients around the wires. The length was $l = 13.5$ mm because the length of the resonator is largely determined by the requirement that the resonant frequency must exceed the plasma frequency. The separation between the line charges was about 3.0 mm since the wire spacing has to be large compared to the sheath thickness in order to minimize sheath effects. The structure was mounted between two magnetic loops using high vacuum epoxy and is electrically floating. The two magnetic loops were attached at the ends of semi-rigid coaxial cables encased in a pyrex tube for vacuum sealing. One of the lines (input) was used for exciting the resonator, the other (output) for detecting the signal coupled to the resonator.

III. EXPERIMENTAL SETUP

The experimental system and the microwave setup for the resonator probe is shown in Fig. 3. The entire assembly was placed in a vacuum chamber through a radial port. The vacuum chamber was evacuated to a pressure of 1×10^{-5} *Torr*. A sweep oscillator (Alfred electronics 633DB) was connected to the input line of the probe. The other line (output) of the probe was connected to a crystal detector (Narda 4503) with frequency response between 0.01 $\sim$ 18 GHz. An SCB device on the holder connected to an external firing set was inserted in the vacuum chamber. The response of the probe as it was swept from 4.0 to 8.0 GHz is displayed in Fig. 4 and the vacuum resonance is about 5.5 GHz, which is in good agreement with (4) which has 5.55 GHz as a value for $l = 13.5$ mm.

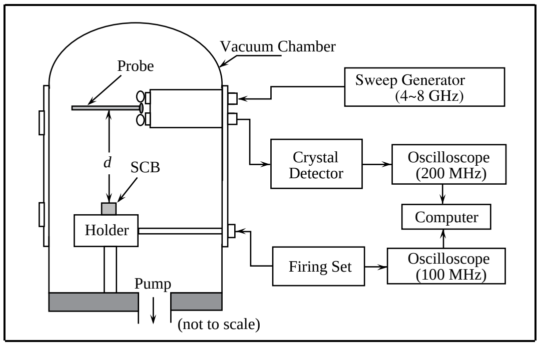

Fig. 3. Experimental system for measuring the density dependent resonator frequency of the microwave probe.

The firing set used in the experiments [8] was a capacitor discharge firing set. It incorporates a fast push-type switch, a capacitor bank (0.24 F), a current viewing resistor (CVR), and a DC power supply. The capacitor bank can produce a constant voltage source if the ca-

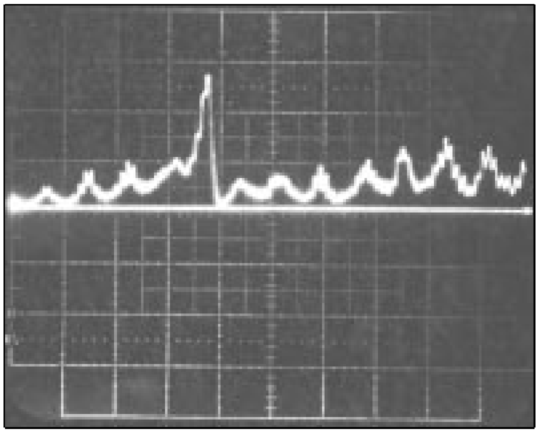

Fig. 4. Microwave resonator probe response, swept 4 to 8 GHz in vacuum. The horizontal and vertical scales are 0.4 GHz per division and 0.1 V per division, respectively. The resonance occurs at 5.5 GHz, which is in good agreement with (4) which has 5.55 GHz as a value for $l = 13.5$ mm.

pacitor is charged to a high voltage so that the SCB firing occurs in a very short time compared with the RC time constant of the firing circuit. The CVR used was 0.01 Ω, which is small so that the potential across the CVR is negligible compared to the potential across the SCB. The distance between the probe and an SCB is d, which is variable.

For a given shot, the resonant structure is excited by a sweep oscillator set to a fixed frequency (4 ~ 8 GHz). The SCB device is driven by an input pulse so that it melts, entirely vaporizing the silicon bridge material, creating a plasma above the bridge. The output of the resonant probe is fed into a crystal detector. A digital oscilloscope (Philips PM3394, 200 MHz) is triggered when the SCB is fired. The probe response is finally displayed on the oscilloscope as a function of time. In addition, the voltage signals V_{SCB} and V_{CVR} are recorded simultaneously on a different fast oscilloscope for the analysis of electrical characteristics.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The presence of plasma expanding from the SCB devices causes a shift in the resonant frequency of the probe. Measurements were performed in vacuum because of the rapid recombination of ions and electrons in air. An example of this measurement is presented in Fig. 5. It is shown that the time-varying density sweeps the resonance frequency through both the buildup and the decay of the plasma at the probe position. The time between the buildup and the decay of the plasma is defined in this work as the *plasma duration* above an SCB device. In this case the plasma duration is 0.3 μs when the applied resonant frequency is 6.8 GHz, corresponding to a density 1.99×10^{11} cm^{-3}.

To determine the peak plasma electron density of an SCB device at a given distance, a number of shots were taken under the same firing conditions with different microwave frequencies. For a fixed microwave frequency, the probe response can be measured as a function of time at a given distance between the probe and an SCB device, as shown in Fig. 6. By varying the frequency, we can measure plasma density variations and obtain a peak plasma electron density by (5) and (6) at a res-

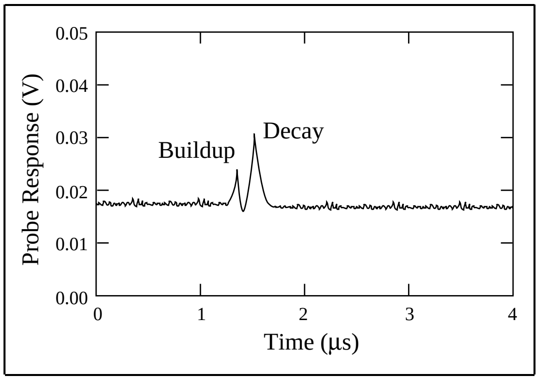

Fig. 5. Oscillograph of the output of the resonator probe excited at a single frequency and responding to the buildup and the decay of the plasma.

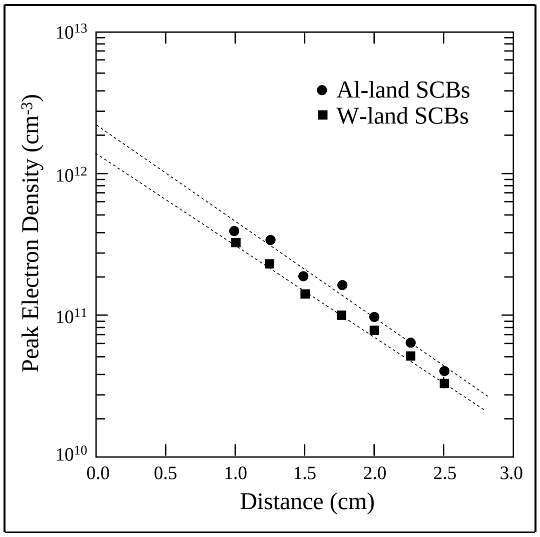

Fig. 6. Peak plasma electron density at the surface of the SCB devices as a function of the distance between the probe and the surface of the SCB device.

onant peak for a fixed distance. By varying the distance, the peak plasma electron densities can be obtained as a function of distance. Finally, we can estimate the peak plasma electron density at the surface of an SCB device by fitting the peak plasma electron density values and extrapolating to zero distance as shown in Fig. 6.

The results of the experiments described above were obtained under the following conditions: Al and W-land SCB devices with $L =$ 47 μm, W = 140 μm, th = 2 μm, R = 1.0 Ω were fired in vacuum employing a capacitor bank 0.24 F capacity charged to 7.0 V. Peak electron densities in the plasma generated from Al and W-land devices are about 2.3×10^{12} cm^{-3} and 1.4×10^{-12} cm^{-3}, respectively. The difference in plasma electron density between the Al and the W-land SCB devices is due to the involvement of the land material. In the Al-land devices, the land region (aluminum) as well as the bridge region (silicon) is melted and vaporized rapidly and completely at a given input energy. In the W-land SCB devices, however, the land region (tungsten) is not vaporized and is not readily sputtered by the ion bombardment of the plasma generated from the bridge with a given input energy.

Once the bridge is melted and completely vaporized, the current flows through the hot vapor above the bridge producing the plasma discharge. We refer to the heating stage of the vaporized material to create a plasma as the late time discharge (LTD) phase of the device operation. Figure 7 displays the plasma electron densities of the Al and W-land SCB devices as a function of input power at the onset of the LTD. We can see that the electron densities in the plasma generated from the Al and W-land SCB devices tend to increase with input energies. Close examination of the land regions of the devices fired showed signs of erosion of the land metal, resulting in the plasma density variations at higher input energies. Note that the density from Al-land SCB devices increases continuously at higher input energies because both the aluminum and silicon are melted and vaporized.

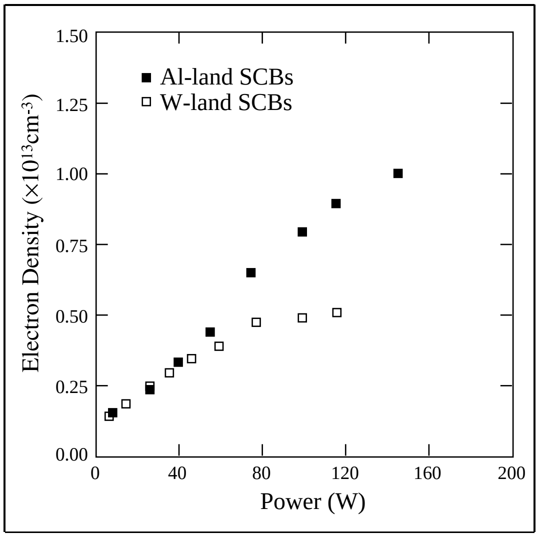

Fig. 7. Peak plasma electron density at the surface of the SCB device as a function of power at the onset of the LTD of the devices with different land materials.

Figure 8(a) shows that the land material begins to erode as well as the bridge material when an appropriate energy is placed in the bridge to vaporize it. A large portion of the land region, especially the cathode land region, is eroded by the higher input energy, as shown in Fig. 8(b). The top contacts of the figures are the cathode land regions during firing of the devices. On the other hand, the density from W-land SCB devices stays constant at higher input energies, presumably because the tungsten does not melt and vaporize, and is not readily sputtered by the energetic ion bombardment of the plasma produced by the higher input energy, as shown in Fig. 8(d). A small portion of sputtering damage on the W-lands after the SCB device operation is evident. Therefore, even though the intense plasma is close to the W-land regions, the amount of sputtered material from the lands is negligible compared to that from the bridge material, resulting in a constant plasma density distribution at higher input energies.

V. CONCLUSIONS

We have utilized a microwave resonator probe to measure the plasma electron density generated by SCB devices. The resonator probe is simple to use and is a sensitive tool for measuring time-varying plasma densities from SCB devices in vacuum. Measured electron densities in the plasma produced by Al and W-land SCB devices are related to the land material and input energy. Although plasma electron densities from Al or W-land SCB devices tended to increase with input energies, at the higher energies, the electron densities produced by W-land SCB devices stayed constant. Therefore, tungsten may be a better land material since it does not suffer from corrosion, low melting temperature, and liquid electromigration as does the case with Al-land SCB devices. Finally, application of these techniques to SCB devices is expected to lead to under-

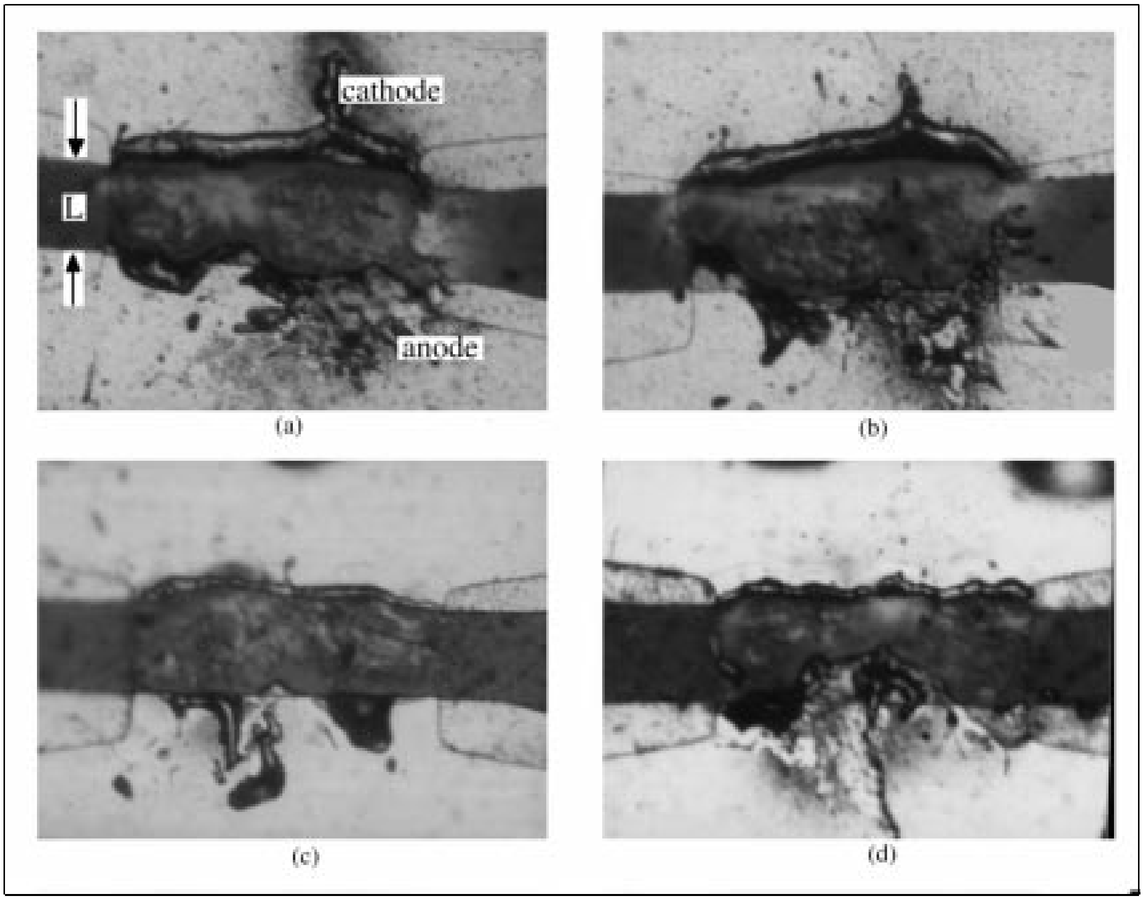

Fig. 8. Microscopic pictures (top view of 200 magnification) of the Al and W-land SCB devices: (a) Al-land SCB device fired with a capacitor of 0.24 F capacity charged to 7.0 V, (b) Al-land SCB device charged to 13 V, (c) W-land SCB device charged to 7.0 V, and (d) W-land SCB device charged to 13 V.

standing the phenomena that cause ignition of an explosive powder.

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REFERENCES

[1] Industry News Update in *Solid State Technology*, vol. 30, p. 40, 1987.

[2] R. W. Bicks, Jr., S. L. Schlobohm and D. W. Ewick, “Semiconductor bridge igniter studies: I. Comparison of SCB and hot-wire pyrotechnic actuators,” *Thirteen International Pyrotechnics Seminar*, Grand Junction, CO, 1988.

[3] D. A. Benson, M. E. Larsen, A. M. Renlund, W.

M. Trott, and R. W. Bickes, Jr., “Semiconductor bridge: A plasma generator for the ignition of explosives,” *J. Appl. Phys.*, vol. 62 (5), pp. 1622-1632, 1987.

[4] J. D. Kim and K. C. Jungling, “Correlated Electrical and Optical Measurements of Firing Semiconductor Bridges,” submitted to *IEEE Trans. on Instrum. Meas.*

[5] J. D. Kim, “Dynamic characteristics of a plasma produced by Silicon-On-Sapphire semiconductor bridge (SCB) under high current density conditions,” Ph. D dissertation, the University of New Mexico, 1994.

[6] J. D. Kim, B. M. Tovar, E. Schamiloglu, and K. C. Jungling, “Measurement of plasma electron density generated by a Semiconductor Bridge (SCB) with aluminum and tungsten lands,” *Proc. of the 15th Symp. on Explosives and Pyrotechnics, Philadelphia*, PA, April 19-21, 1994, pp. 1.1-1.8.

[7] P. W. Werner and E. Schamiloglu, “Measurement of electron density in a laser-generated channel,” *Proc. of the 14th Symp. on Discharge and Elect. Insulation in Vacuum*, Santa Fe, NM, 1990, p. 759.

[8] J. D. Kim, E. Schamiloglu, B. M. Tovar, and K. C. Jungling, “Temporal measurement of plasma density variation above a semiconductor bridge (SCB),” accepted for the Aug. 1995 issue of *IEEE Trans. on Instrum. Meas.*

[9] J. D. Kim, B. M. Tovar, E. Schamiloglu, and K. C. Jungling, “Measurement of plasma electron density generated by a Semiconductor Bridge (SCB),” *Electron. Lett.*, vol. 30, no. 7, pp. 603-604, 1994.

Jongdae Kim received the B. S. and M. S. degrees in electronic engineering from Kyungpook National University, Taegu, Korea in 1982 and 1984, respectively. He received the PH. D. degree in electrical and computer engineering from the University of New Mexico, Albuquerque, NM in 1994. From 1984 to 1988, he was with the Electronics and Telecommunications Research Institute (ETRI) in Korea, where he worked on silicon based device design and process integration of EEPROM and CMOS. In 1994 he joined the ETRI as a senior research engineer and is currently engaged in research of semiconductor device physics and modeling.

K. C. Jungling is a chairman of the Department of Electrical and Computer Engineering at the University of New Mexico. His research intersts include the design and fabrication of semiconductor devices and integrated circuits with a recent emphasis on submicron devices and circuits.