MEMS Electric-Field Probes for Laboratory Plasmas

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***Abstract*—This paper presents microfabricated sensors for directly measuring fine-scale plasma parameters in typical laboratory plasmas. Microfabricated probes have the potential to significantly advance basic plasma physics by enabling the measurement of fundamental processes under controlled conditions. Historically, the spatial scales of the finest electromagnetic-field fluctuations in laboratory plasmas have been too small for conventionally fabricated tools to sense. The new probes are arrays of electric-field sensors for measuring Debye-scale structures in the Large Plasma Device (LAPD) at the University of California at Los Angeles. Typical Debye lengths in the LAPD are 25 μm, with electron gyroradii of about twice that value. The probes are constructed of polyimide, chrome, and gold; have electrode widths ranging from 8 to 20 μm; are 23 μm thick; and are spaced 40 μm apart. The probes are wirebonded to a printed circuit board with commercial amplifiers, and the ensemble is placed inside the plasma chamber. The frequency response of the measurement system extends to 1 GHz. The probes have been used to measure the electric fields of interesting structures in the LAPD. [2008-0230]**

***Index Terms*—Electric-field measurement, microelectromechanical devices, plasma devices, plasma measurements.**

I. Introduction

A. Motivation

OF THE visible matter in the universe, plasma, or ionized matter, is believed to make up a very large fraction, perhaps over 99%. Plasmas underpin the $250 billion semiconductor processing industry, support the $2 trillion telecommunications industry, and are becoming increasingly important to lighting, medicine, and consumer products [1]. However, despite the broad utility and widespread presence of plasmas, there are a great many fundamental unknowns in plasma science. One of the experimental reasons for these unknowns is the difficulty of measuring basic plasma parameters, such as temperature, density, electromagnetic fields, and pressure fluctuations, under controlled conditions. Building instrumentation for measuring plasmas must balance two competing concerns: first, controlling the conditions of the plasma; and second, matching the speed and size of the instruments to the phenomena of interest. Key spatial characteristics of plasmas scale with temperature and density. Many of the most important observations of plasma behavior have been made with instruments integrated into rockets, satellites, or spacecraft in cool and diffuse space plasmas where the spatial scales may be meters or larger. Unfortunately, spacecraft measure only the plasma conditions they chance to pass through, usually with no ability to orient themselves or direct themselves relative to interesting plasma activity. The situation is reversed for almost all terrestrial plasmas of interest: it is easy to control experimental conditions, but many interesting phenomena are too small for conventionally fabricated sensors. The use of microfabricated instrumentation in laboratory plasmas combines plasma control with spatial resolution in ways that could revolutionize basic plasma science.

B. Background

Microfabricated sensor systems for plasma diagnostics have existed for some time, particularly for process analysis in the semiconductor industry. Sensors fabricated directly on silicon wafers allow semiconductor wafer-processing tools to handle diagnostic systems as if they were production wafers [2]. Instruments integrated onto wafers include temperature and film-thickness sensors, heat-flux probes [3], [4], impedance-tomography probes [5], ion-flux sensors for 2-D flux characterization, and other sensors [6]–[8]. However, these process tools were designed for chamber or wafer-scale measurements. Microfabrication techniques have not yet been applied to the field of basic plasma science or achieved the much finer level of resolution necessary for measurement of many basic plasma parameters.

One of the key spatial parameters of a plasma is the Debye length, the characteristic physical scale on which the charged particles that compose the plasma move to shield an introduced electric field from the bulk of the plasma. Fig. 1 shows Debye lengths of plasmas over a range of temperatures and densities. In magnetized plasmas, additional characteristic lengths are the plasma gyroradii, the radii of orbit of charged particles around magnetic-field lines. Many plasma phenomena of scientific and practical interest occur over distances that scale with the Debye length or gyroradii.

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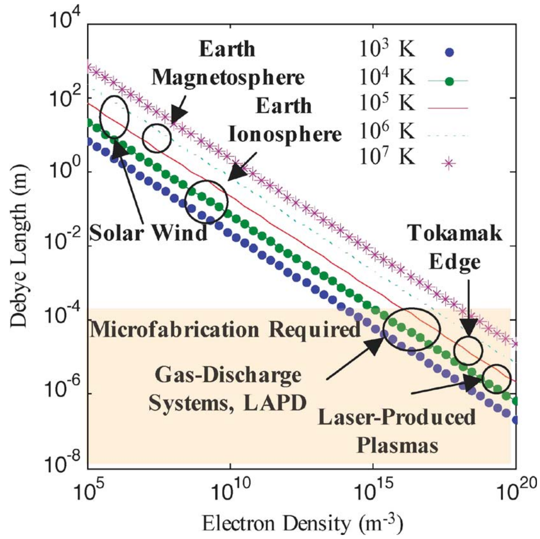

Fig. 1. Debye lengths of some types of plasmas as a function of temperature and density.

This paper describes the design, fabrication, and electrical characterization of microfabricated sub-Debye-length probes for measuring the electric field in the Large Plasma Device (LAPD) at the University of California at Los Angeles. Some experimental results are also presented, although greater detail on some measurements can be found in [9].

The probes were developed specifically to measure the electric fields of laboratory-based electron solitary structures (ESSes). An ESS, as measured by satellites in space, is characterized by an abrupt localized decrease in the electron density [10]–[15]. Although spacecraft measurements have only detected this phenomenon along one direction of travel at a time, some ESSes are believed to be vortices in the spatial and velocity distributions of the electrons. Models of these ESSes suggest that electrons oscillate around the core of the ESS after becoming trapped in a potential well around it. These oscillating, trapped electrons linger longer at the turning points of their orbit than they do passing through the center, where they have the highest kinetic energy. The velocity difference between electrons on the edges of the ESS and electrons in the center results in an electron-density difference. The concentration of positively charged ions is constant. From a distance, the positively charged core, which has a low density of electrons, and the negatively charged cloud around it, where the electron density is high, are charge-neutral.

The majority of ESSes measured in space have been a few Debye lengths across [11]–[13]. Computer simulations also find that ESSes are commonly of this size [16], [17]. Thus, electric-field measurements of ESSes in laboratory plasmas call for microfabricated probes with dimensions on the order of or smaller than the plasma Debye length.

II. Design of Electric-Field Microprobes

A. Electric-Field Microprobe Architecture

Under low-frequency, quasi-static conditions, measuring the gradient of the electric potential gives the electric field. However, when an object larger than the Debye length is introduced into a plasma, a sheath forms in the local plasma potential surrounding the object [18]. The presence of this sheath is particularly troublesome when attempting to measure fluctuating electric fields inside plasmas: in many cases, voltage probes measure the voltage of the sheath caused by the insertion of the probe rather than the voltage of the undisturbed plasma several Debye lengths away. A more intensive discussion of this phenomenon and various electric-field-probe architectures can be found in [9]. To summarize the conclusions drawn there, probes that are smaller than a Debye length do not disturb the plasma.

Ideally, a complete electric-field measurement system would be smaller than the plasma Debye length and the gyroradii in all directions. Unfortunately, the current state of technology does not yet permit the immediate fabrication of a complete, self-powered, appropriately positioned system that is smaller than the LAPD Debye length ($\sim$25 μm) in all directions. Instead, the microfabricated probes were modeled on the architecture of electric-field probes that have successfully measured ESSes in space [10]–[15], [19] but scaled down for the anticipated spatial and temporal scales of ESSes in the LAPD plasma. The space probes consisted of sensor heads that were small relative to the local plasma Debye length but that were tethered some distance from much larger objects (the satellites or spacecraft). The microprobes mimicked this arrangement: they were smaller than the local plasma Debye length along the direction of measurement but were tethered to plasma-chamber feedthrough shafts that were much larger than the Debye length. The shafts were also larger than the plasma gyroradii and therefore generated turbulence. The microfabricated tethers were thus required to suspend the sensing electrodes many Debye lengths away from the ends of the shafts.

In both types of systems, the sensor heads themselves were simply metal electrodes exposed directly to the plasma. For measuring the gradient of the electric potential of ESSes a few Debye lengths across, the microfabricated electrodes were spaced approximately a Debye length or less apart.

B. Electric-Field Microprobe Design Requirements

The spatial scales in the LAPD plasma set many of the requirements for the microfabricated probes. For the ESS experiments with these probes, the LAPD plasma had a Debye length of 20–30 μm, an electron gyroradius of 50–100 μm, and an ion gyroradius of about 2 mm.

The LAPD [20]–[22] is an 18-m-long, 0.6-m-diameter column in which a dc discharge produces the plasma. The density ranges from 10^{15} to $3 \cdot 10^{18}$ m^{-3}, and the electron temperature (thermal energy) ranges from 0.25 to 15 eV ($4 \cdot 10^{-20}$ to $2.4 \cdot 10^{-18}$ J). The plasma duration is approximately 10 ms with a pulse rate of 1 Hz. The plasma in the LAPD is highly magnetized, with the axial magnetic-flux density ranging from below 0.03 T to as high as 0.3 T. Experiments at lower temperature and density can also be performed in the afterglow plasma when the discharge has been shut off. In the afterglow plasma, the electron temperature (thermal energy) rapidly decays to several tenths of an electron volt (several tens of 10^{-20} J), and the density decays on a much smaller timescale.

The discharge plasma is highly ionized and electron–ion Coulomb collisions are the only collisions of importance. The collision frequency is approximately 500 kHz. The plasma is quiescent, with density and temperature fluctuations of several percent, and highly reproducible from shot to shot. No large-scale flows or drift develop in the plasma bulk.

Design requirements for the sensitivity and frequency range of the microprobes came from scaling down measurements of larger scale ESSes. The peak voltages in most ESS measurements both in space and in the laboratory were close to the average electron potential. For example, in Viking satellite measurements of plasmas with electron thermal voltages believed to vary between 1 and 10 eV (energies between $1.6 \cdot 10^{-19}$ and $1.6 \cdot 10^{-18}$ J), voltage signals ranged from about 2.5 V down to about 0.2 V [23]. In [24], the measured peak voltage in a 0.2-eV plasma (with a thermal energy of $0.32 \cdot 10^{-19}$ J) was about 0.1 V. The typical electron thermal energy in the LAPD is 7 eV $(11.2 \cdot 10^{-19}$ J). These previous measurements suggest that ESS-generated signal magnitudes on the order of about 1 V for electrodes spaced approximately a Debye length apart should be expected in the LAPD.

The expected traveling speeds and dimensions of the ESSes determined the frequency specifications for the microprobes. ESSes in space have been observed to move at 0.1 to 0.5 times the plasma electron thermal speed. To faithfully transmit voltage spikes due to the passage of the smallest, fastest ESSes past the most closely spaced probe electrodes of the experiment under typical LAPD conditions would require a frequency response that extended to tens of GHz. Instead, an upper frequency of 1.8 GHz was selected for this generation of probes. The 1.8-GHz upper limit permitted the use of inexpensive, off-the-shelf, discrete amplifiers. To accommodate the frequency limitation, the plasma temperature was lowered somewhat from its usual operating point to reduce the plasma thermal speed. At 1.8 GHz, the probes should be adequate for recording the electric fields of ESSes with diameters of a few tens to a few hundreds of micrometers traveling at speeds near 10^5 m/s.

An additional concern of scaling down conventional probes was the mechanical resonant frequency of these small devices. In the high-vacuum plasma chamber, any undamped mechanical resonance could cause spurious electrical measurements. The probes were required not to have any mechanical or electrical resonant peaks within or near the signal band.

In the magnetized plasma of the LAPD, two directions of measurement were necessary to initially characterize the electric field: first, parallel to the magnetic field; and second, along one additional axis perpendicular to the magnetic field.

The probes were also required to be compatible with the LAPD digitization equipment and the vacuum-interlock diagnostic ports through which probes can be inserted or withdrawn while the LAPD is running. The LAPD probe shafts that can be inserted through the vacuum feedthroughs are 1–3-m-long stainless-steel tubes. Because of the great length of the probe shafts, measurement of high-impedance signals at the probe electrodes required amplification electronics to be located near the probe electrodes themselves, which are inside the plasma chamber. The amplification circuits also offered an opportunity to present a 50-Ω output impedance for convenient transmission along cables, connectors, and to the 50-Ω digitizer inputs. Electronics inserted into the plasma chamber also require cooling. Previous experiences with uncooled circuit boards inserted into the LAPD plasma have shown that the operating temperature of the circuit boards rises as high as 150 °C and melts solder, even for electrical power dissipation as low as a few tenths of a Watt.

Finally, the amplifier circuits and the signal lines connecting the probe electrodes to the amplifier circuits required physical and electronic shielding to protect them from the intense heat and particle fluxes, magnetic fields, and RF and microwave radiation of the plasma. The target value for the capacitive coupling of the wires to the plasma was less than 5 pF for the entire length of the wire between the sense electrode and the wirebond pad.

Table I summarizes these requirements as well as the fabrication choices.

TABLE I
DESIGN REQUIREMENTS OF MEMS PROBES FOR MEASURING VOLTAGE AND ELECTRIC FIELDS IN A HIGH-DENSITY LABORATORY PLASMA WITH A DEBYE LENGTH OF APPROXIMATELY 25 μm

Parameter	Target Range	Fabricated Result
Electrode Width	~1 Debye length (25 μm)	8 to 20 μm
Electrode Thickness	< 1 Debye length (25 μm)	2.5 μm
Intrapair Electrode Spacing	~1 Debye length (25 μm)	20 to 52 μm
Interpair Electrode Spacing	~1 Debye length (25 μm)	40 to 108 μm
Electrodes per Chip	> 4	8
Wire Capacitance to Plasma	< 5 pF	3 pF (estimated)
Electrode-to-Pad Resistance	< 25 Ω	22 Ω
Distance from Electrode to Copper Box	1 cm	> 1 cm
Maximum Operating Temperature	>150 °C	600 °C (advertised polyimide degradation temperature)
Mechanical Resonance Frequency	< 200 MHz or > 2 GHz	370 Hz (estimated)

III. FABRICATION

A. Preamplification Circuits

A custom four-layer printed circuit board (PCB) using a 1.8-GHz commercial amplifier (THS4303, Texas Instruments Incorporated, Dallas, TX) was fabricated to preamplify the sensed plasma signals and drive the long probe-shaft cables. To avoid the noise of the plasma-excitation system, other low-frequency noise, and the dc plasma bias of several volts, the probe connectors were coupled to the amplifier through a one-pole high-pass RC filter with a 3-dB frequency at approximately 5 MHz. To ensure that most of the signal voltage fell across the preamplifier inputs rather than the probe-to-preamplifier wiring, the wiring was designed with a parasitic capacitance of less than 5 pF and a resistance of less than 25 Ω. The signal voltage dropped across a 1-kΩ input resistance to ground.

During plasma measurements, a custom-built copper box [Fig. 2(a)] protects the electronics from the plasma. A screw-on lid seals the top of the copper box. To cool the electronics, pressurized air is forced through a copper tube folded in half, with

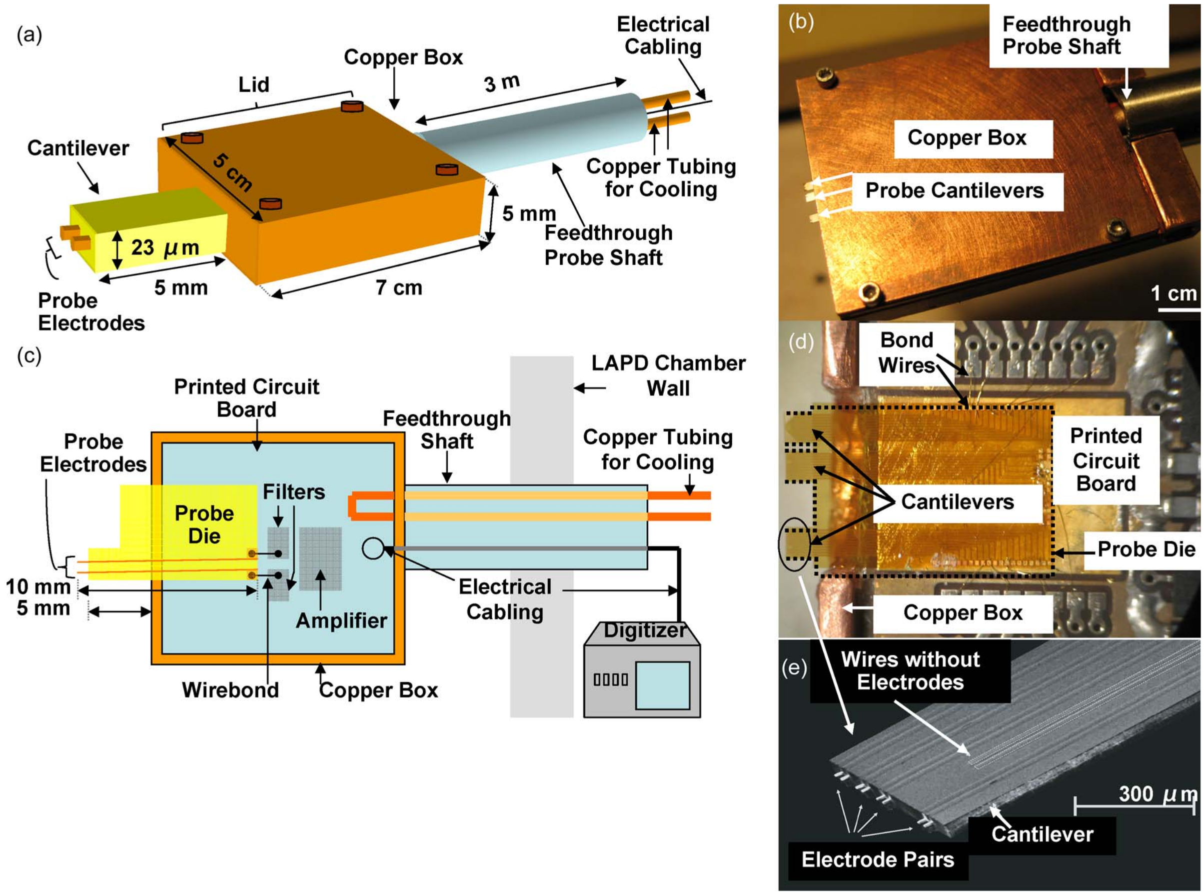

Fig. 2. (a) Schematic (not to scale) of an electric-field probe system, showing the probe die, the copper box containing the electronic amplifiers, and connections to the vacuum feedthrough shaft. (b) Photograph of the fabricated box with the lid screwed and a probe die protruding from the front. (c) Top schematic view of the probe system with the lid of the copper box removed. (d) Closeup photograph of the probe die glued to the PCB inside the copper box with the lid removed. The cantilevers will protrude into the plasma when the lid is attached. (e) SEM of a cantilever containing four electrode pairs that will be exposed to the plasma and one dummy pair of wires.

the hairpin turn of the tube inserted through the probe shaft. The signal and power wires enter the copper box through a hole on the back end of the box, where they are soldered onto the PCB. The probe chip is then glued onto the opposite end of the PCB, so that it protrudes from a second hole in the front of the copper box, where it is exposed to the plasma. Wirebonds connect pads on the microfabricated probe die to pads on the PCB [Fig. 2(b)]. After making the electrical connections, the lid of the copper box is attached. Plasma-resistant epoxy seals the front and rear openings of the box to isolate the PCB and feedthrough shafts from the plasma. Contamination of the plasma chamber by the box and probes is avoided by pumping the box down in an interlock chamber to 2 μtorr before introduction into the LAPD chamber.

The copper box is about 5 mm high, 7 cm long, and 5 cm wide, large enough to disturb the plasma under measurement. Cantilevers on the probe chips suspend the sensing electrodes away from the box (Fig. 2). For the initial tests, the cantilevers held the probe tips 5 mm (about 200 times the Debye length) from the end of the box.

B. Microprobes

To measure the electric field at several points along the magnetic field, several sets of electrode pairs were arrayed in a line [Fig. 2(e)]. Although the schematics in Fig. 2(a) and (c) show single pairs of electrodes in a single cantilever for clarity, in fact each probe die held three cantilevers [Fig. 2(b) and (d)], and each cantilever contained four to eight electrode pairs [Fig. 2(e)]. Multiple sizes of differential pairs of probe tips were fabricated. The electrode widths ranged from 8 to 20 μm, with the two tips of a single pair spaced from 20 to 52 μm apart. Tips of adjacent pairs were separated by 40–108 μm.

Electrode pairs were also interspersed with wire pairs that lacked exposed electrodes [Fig. 2(e)], permitting comparison of signals from the electrodes to signals picked up by the wiring or other sources. Most of the probes were designed to measure the electric field along the magnetic field of the chamber, but pairs of probes were also included for measuring the electric field perpendicular to the magnetic field (not shown).

The probes and wiring were mechanically supported and electrically insulated by embedding them in a 23-μm-thick cantilever of low-stress polyimide (PI-2600, HD Microsystems, Parlin, NJ). This polyimide has an advertised glass-transition temperature of 350 °C and does not begin to physically degrade until 620 °C. It is also mechanically stiff for a polyimide, with an elastic modulus E of 8.5 GPa. The polyimide and gold sandwich has proven nearly indestructible under normal handling and processing conditions. In addition, with a mass density ρ of about 1.4×10^3 kg/m^3, the polyimide cantilever has an

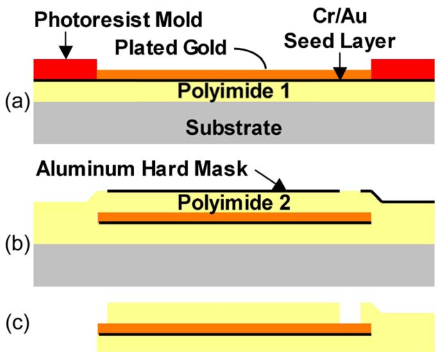

Fig. 3. Two-mask fabrication process for voltage and electric-field probes (not to scale). (a) A thin chrome–gold seed layer is evaporated onto a 10-μm-thick layer of polyimide. Mask 1 forms a mold for a thick layer of electroplated gold. (b) The seed layer is etched away except where protected by the electroplated gold, and a second layer of polyimide is spun on. An aluminum hard mask is evaporated and patterned to define the boundaries of the probe dice and to expose the electrodes and bondpads. (c) The polyimide is etched, then the hard mask is removed, and the dice are peeled off the substrate.

estimated mechanical resonant frequency in vacuum of about 370 Hz, well below the frequencies of interest. The resonance-frequency estimation models the cantilever as a thin beam with a rectangular cross section, with resonance frequency f_r given by

$$f_\mathrm{r} = \frac{1}{2 \cdot \pi}\sqrt{\frac{k}{0.24 \cdot m}} = \frac{h}{2 \cdot \pi \cdot l^2}\sqrt{\frac{E}{0.24 \cdot \rho}} \qquad (1)$$

where k is the cantilever spring constant, m is the cantilever mass, and h and l are the thickness and length of the cantilever, respectively [25]. This calculation ignores the mass and spring resistance of the gold wires, which are much smaller than the mass and spring constant of the polyimide structure.

With a relative permittivity of 2.9, a 10-μm-thick layer of this polyimide is sufficient to yield a capacitance between the 1-cm-long, 32-μm-wide probe *wire* and the ambient plasma of less than 3 pF. The total thickness of the cantilever is thin enough not to cause significant disturbance. The cantilever is just over 1 mm wide, which is narrower than the ion gyroradius and, therefore, not expected to be a significant source of disturbance to the magnetized plasma under test conditions. This size balances the desire for multiple adjacent probes measuring the electric field in several directions, as well as the dummy tipless probes, with the desire for a small form.

Gold was the material of choice for the probes, as it is easily wirebondable. In addition, unlike aluminum, gold forms no significant oxide layer and so is easier to model. Gold also has a low magnetic permeability, is ductile, and has a low enough resistivity to achieve the needed resistance in 1-cm-long, 2.5-μm-thick, and 20–32-μm-wide wires.

The two-mask fabrication process began by spinning a 10-μm-thick film of polyimide onto a silicon carrier wafer [Fig. 3(a)]. The polyimide surface was then roughened by etching in a photoresist asher (Plasmaline 515, Tegal, Petaluma, CA, U.S.) to improve adhesion of the following metal layer. A seed layer, consisting of 10 nm of chrome and 30 nm of gold, was then evaporated onto the wafer. A 6.5-μm-thick photoresist film (Microposit SJR 5740, now Rohm and Haas, Philadelphia, PA, U.S.) acted as a mold for electroplating a 2.5-μm-thick layer of gold [Fig. 3(a)]. The gold was electroplated with a commercial solution (AR434 RTU Pure Gold, Technic, Inc., Cranston, RI) at room temperature with a current density of 1 mA/cm^2.

After stripping the photoresist and etching the unplated regions of the seed layer, the wafers were submerged in a bath of isopropyl alcohol for 5 min to improve the adhesion of the next layer of polyimide. The polyimide was again roughened in an oxygen plasma, and a second 13-μm-thick layer of polyimide was spun on.

A second mask [Fig. 3(b)] defined the bondpad openings in the top layer of polyimide, exposed the sensing electrodes, and defined the individual dice. The mask was a 50-nm-thick evaporated aluminum film patterned by lift-off. The wafer was etched in 100% oxygen plasma at 0.2 torr in a reactive-ion etcher (Oxford Instruments, Bristol, U.K.).

After the oxygen-plasma etch, some polyimide residue remained on the exposed gold pads and tips. This "microlace" made wirebonding difficult. A 5-min etch in 15% CF_4 and 85% O_2 cleaned off the pads and tips, at the expense of a few hundred nanometers of gold. The hard mask was then removed.

In the final fabrication step, the polyimide and gold chip was gently peeled away from the carrier wafer [Fig. 3(c)] and glued to the preamplification board. Removing the chip was found to be straightforward if adhesion promoter for the polyimide (HD MicroSystems VM-652, Parlin, NJ, U.S.) was applied only to the outermost 5 mm of the carrier wafer, before the first layer of polyimide was spun on. The ring of adhesion promoter held the polyimide to the wafer during processing but allowed for an easy release after the final oxygen plasma etch. The yield for this process was nearly 100%.

IV. Electrical Characterization

The measured total tip-to-pad resistance for an 8-μm-wide tip and a 32-μm-wide wire was 22 Ω at dc.

Because the probe tips must, by design, be unsupported, it was not possible to measure the electrical behavior of the complete system, including the amplifiers, copper box, and probe shafts, directly with an RF probe station. However, as a sanity check, the frequency response of six individual voltage probes on a chip mounted in a copper box and wirebonded to the populated PCB was measured. One of the wires embedded within the polyimide cantilever that lacked exposed probe tips was also tested. A short piece of wire protruding from a terminated 50-Ω cable was driven by a network analyzer (8753D, HP, Richardson, TX) and placed near the probe die, capacitively coupling it to the electrodes. The results of the probe characterization are shown in Fig. 4. The frequency response is relatively flat to just above 1 GHz (the amplifiers function up to 1.8 GHz). We suspect that the reduced performance above 1 GHz is due to the inductances of the long wirebonds combined with the circuit-board layout.

V. Results

The electric-field probes were used to sample the electric field in a narrow current sheet in the center of the LAPD. Data were acquired with an 8-GHz analog-input oscilloscope in 200-μs-long data records (32 megasamples) that included the

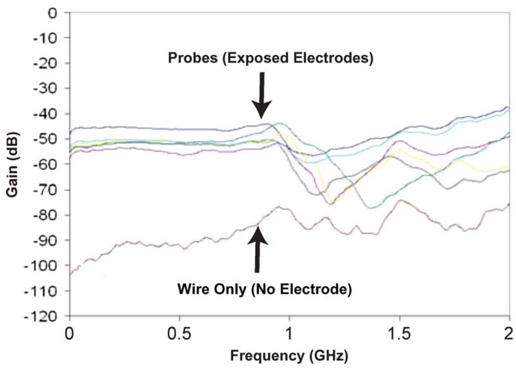

Fig. 4. Frequency response of six individual voltage probes and a probeless wire mounted on a preamplifier circuit board and driving the probe-shaft feedthrough wiring.

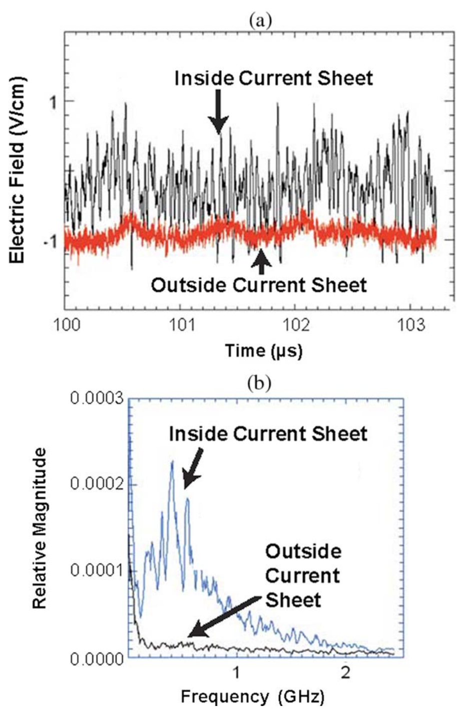

Fig. 5. Electric-field measurements of probes in a plasma current sheet. (a) Electric-field fluctuations over time. (b) Spectral plot of the time sequence shown in (a).

initial switch-on of the current sheet. The probes could be moved around inside the plasma chamber by changing the angle of the probe shaft. Fig. 5(a) shows an example recording of the electric field sensed by probes oriented perpendicular to the LAPD magnetic field. The data were collected using the probes for which the electrical characterization was shown in Fig. 4. The recordings were taken with the probes positioned both inside and outside the current sheet, 100 μs after the current was switched on. When removed from the current sheet (but still within the plasma chamber), the activity recorded by the probes flattened to a few tens of millivolts per centimeter peak-to-peak. When inside the current sheet, the probes measured electric-field spikes traveling near the electron thermal speed, as anticipated for ESSes. The electric-field spike magnitudes were approximately 1 V/cm. Fig. 5(b) shows the frequency spectrum of the same signals.

VI. Conclusion

A set of microfabricated sub-Debye-length plasma probes that can be used to measure electric fields in laboratory plasmas without disturbing the plasma was demonstrated. It is clear from the initial tests performed with these MEMS probes at the LAPD that there are many previously unobserved phenomena waiting to be characterized and explained. Improvements to these probes, as well as other probes, such as a micrometer-scale ion-energy analyzer, are presently in development and testing. We hope that these tools will significantly improve the ability to measure fundamental parameters of plasma behavior and that this improvement will lead to the optimized use of plasmas for a wide range of economically significant applications.

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