# Submicron gap capacitor for measurement of breakdown voltage in air

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We have developed a new method for measuring the value of breakdown voltage in air for electrode separations from 400 nm to 45 $\mu$m. The electrodes used were thin film Au lines evaporated on sapphire. The resulting capacitors had an area of $80 \times 80$ $\mu m^2$. We demonstrate the ability to deduce the value of the separation of the plates by the value of the capacitance. The data acquired with this method do not agree with Paschen's law for electrode separations below 10 $\mu$m, as expected from previous experiments. Amongst the improvements of our method are the measurement of plate separation and the very small surface roughness (average of 6 nm). *© 2006 American Institute of Physics.* [DOI: 10.1063/1.2185149]

## I. INTRODUCTION

The understanding of electrical breakdown of air between electrodes that are separated by very small gaps is important for technological reasons. In the microelectronics industry circuits are becoming increasingly dense. In microelectromechanical systems (MEMSs), for example, spacing between conductors is of the order of a few microns, or below. In these types of devices, high voltages are usually applied across such small gaps of air.[1,2] Electrical breakdown, which leads to leakage currents, can be detrimental to their operation. Clearly, the knowledge of the value of the breakdown voltage and the parameters that affect it will be an important consideration for their design, as well as their operation. The value of the breakdown voltage can also be of interest in areas such as automobile electrical systems, or even circuit breakers designed for household use.[3]

Recently a small number of studies have been done in the regime of such small air gaps.[3–6] The main conclusions of these studies were that for small separations between conductors, Paschen's law no longer applies. Paschen's law describes the avalanche mechanism, responsible for electrical breakdown, for macroscopic separations between the electrodes. It states that the absolute minimum value for the breakdown voltage of air, for uniform fields, is 360 V.[7] Also, device geometry and surface roughness of conductors play an important role. Device geometry determines the shape of the electric field lines between the two conductors. Complicated geometries such as needlelike electrodes produce electric fields that vary substantially with position. Surface roughness causes field amplification on the surfaces of the electrodes. The combination of these two reasons makes the interpretation of experimental results challenging.

In order to understand the mechanisms of breakdown better in the regime where Paschen's law no longer applies, more experiments with simpler geometries are needed. In contrast to previous experimental methods, our method for measuring the breakdown voltage of air has the following improvements: (1) it allows us to measure the distance between the two conductors before each measurement and change it in a range between 400 nm and 45 $\mu$m, (2) it has a parallel plate geometry with a large plate area to distance ratio, which will produce nearly parallel field lines, and (3) because the conductors used were evaporated thin Au films, the surface roughness is significantly better than typical bulk metal conductors commonly used in previous experiments. The average surface roughness of our Au films, as deposited on a sapphire substrate polished to an optical finish, is 6 nm.

## II. SAMPLE FABRICATION AND ASSEMBLY

Our samples are Au lines, 80 $\mu$m wide, deposited on sapphire substrates. A picture of a sample is shown in Fig. 1, along with a profilometer scan across the Au line. All samples have the same "horseshoe" pattern with large contact pads on each end, so that the measurement of the electrical continuity of the line is possible at any time during the experiment. This is important because the lines often become electrically discontinuous as a result of the breakdown. The samples were designed so that the final air gap capacitor would have the desired plate spacing without the use of complicated mechanical systems. $SiO_2$ was used as a spacer between the samples. Sapphire was used as the substrate because of its hardness, which allows the application of forces without significant bending. In addition, its transparency proves useful in the alignment of the final device.

We start with commercially available sapphire substrates of 22.5 mm in diameter and 3.3 mm in thickness. A thin film, usually 80 nm thick, of $SiO_2$ is deposited with a plasma-enhanced chemical-vapor deposition (PECVD) method. We spin-coat the sample with photoresist, and with photolithography and development we remove the resist from where we want the pattern to be. The sample is then dipped in HF until the $SiO_2$ under the openings in the resist has been etched away.

A thin layer of Cr (about 3 nm thick) followed by a layer of Au is then evaporated on the sample. Cr was used to promote adhesion to the substrate. After lift-off, Cr and Au are left only in the previously defined trench. The thickness

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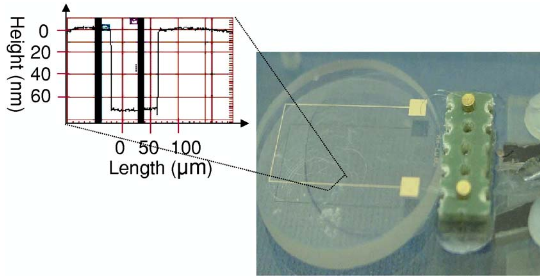


FIG. 1. Picture of a sample. The Au line is 80 $\mu$m wide, with contact pads at each end. There are wire bonds connecting the pads to Au posts on a plastic support. The insert is a profilometer scan, perpendicular to the Au line. The depth of the trench was chosen to be 70 nm for this sample.

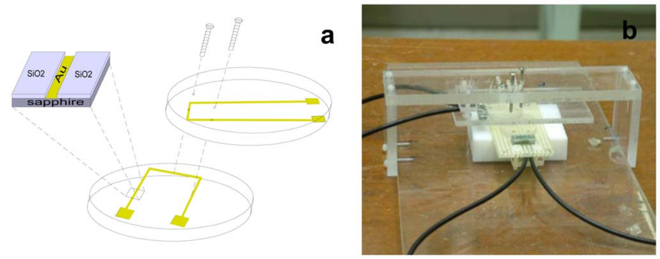


FIG. 3. (a) A schematic representation of two samples coming together, forming the air gap capacitors at each crossing point. (b) A photograph of an assembled device. Two samples on plastic supports are brought together and pushed by metallic screws.

of the Au film determines how "deep" the final trench is. In the profilometer scan in Fig. 1, for example, that value was chosen to be 70 nm. The surface roughness of the Au film, as measured by atomic force microscopy (AFM) scans, was 6 nm on average, with a maximum peak-to-trough height of about 60 nm. An example of such an AFM scan is shown in Fig. 2. The samples are then mounted on plastic supports with electrical leads. For electrical contact we used Al–Si wire bonds, shown in Fig. 1.

To assemble the air gap capacitor we use two samples. One sample is flipped, compared to the other and they are brought together so that the line on each one is perpendicular to the other. That creates two parallel plate capacitors for each device. A schematic of how the samples are brought together is shown in Fig. 3(a). A picture of the final device is shown in Fig. 3(b).

## III. USING THE VALUE OF THE CAPACITANCE TO ASCERTAIN THE VALUE OF THE PLATE SEPARATION

In order to understand how the capacitance of the two Au lines depends on the distance between them, we simulated the capacitance versus separation using a commercial software package. The results of the simulation are shown in Fig. 4. The capacitance of the device can be separated in two different parts. The first part is due to the parallel plate capacitor created by the crossing of the two Au wires. The second part is due to the capacitance of the remaining parts of each of the lines. For large separations the second part dominates. Below a separation on the order of the Au line size, that part of the capacitance changes slowly with distance and the parallel plate part begins to contribute significantly to the total capacitance. For small separations, the parallel plate part dominates. The simulation shows that the electric field always has its maximum value in the area of the crossing between two Au lines. We took two samples that were brought together by the method described above and attached the top one to an $x$-$y$-$z$ translator. We could thus control the distance between the two Au lines, the plates of the capacitor, with a micrometer precision. The capacitance of the system was measured using a capacitance bridge, which rejects stray capacitance caused by the wires. A coaxial cable is used for the leads of the capacitor and the switch box was constructed so that all cables used are electrically shielded. Also, all supports used were plastic, so that

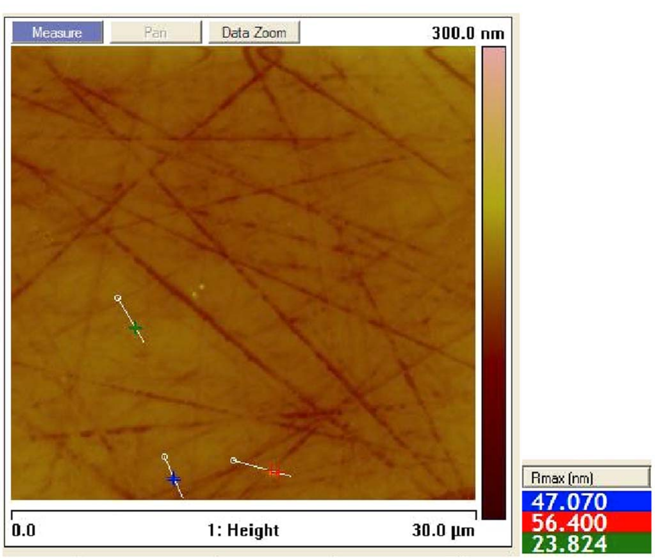


FIG. 2. Example of an AFM scan of the Au surface. The line scans on the picture, which are indicated by white lines, were chosen to run over the spots of maximum height. The insert lists the values of the difference between the maximum and minimum heights for each line scan.

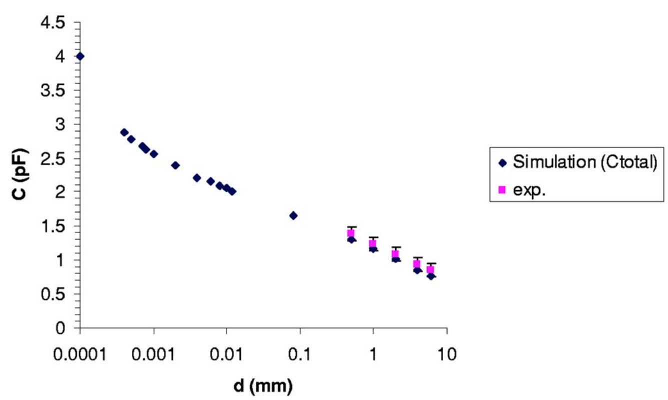


FIG. 4. Capacitance ($C$) of the air gap capacitor as a function of electrode separation ($d$). The experimental data were taken by controlling the position of one of the electrodes with an $x$-$y$-$z$ translator. The presence of the translator shifts the value of the capacitance and so an experimental uncertainty of ±0.1 pF is introduced. For spacings of 6–0.6 mm the experimental data agree with the simulation values, within the experimental uncertainties. We thus conclude that the simulation is an accurate description of the real capacitance down to 400 nm.

the value of the capacitance measured was not altered by stray fields. The capacitance versus distance measurements are also shown in Fig. 4.

It is obvious that the data agree with the simulation. From this, we conclude that by doing a capacitance measurement between the two Au lines, and using the simulation curve, we can accurately determine the distance between them. Furthermore, we can extrapolate this method to small values of separation, where a direct measurement of the distance is not possible. A capacitance measurement allows us to infer the distance between the Au lines for all distances.

## IV. EXPERIMENTAL SETUP

Nominally, if two samples were brought in contact with the method described in Sec. II, the separation between the lines would be twice the distance between the upper surface of the $SiO_2$ and the Au film on the samples used. However, because the sapphire windows are not perfectly flat, that separation is, in reality, substantially larger. In order to bring the plates closer together, we bring the two samples in contact and then use screws to apply force over the regions where the lines cross. For the determination of the value of the breakdown voltage we want to measure the current through the capacitor as a function of the voltage applied to it. The circuit for the breakdown measurements consists of a dc voltage source, the capacitor, and a 10 MΩ resistor in series. A voltmeter monitors the potential drop across the resistor in order to determine the current. A switch box allows us to change from a breakdown measurement to a capacitance measurement, which determines the value of the plate separation.

Before each breakdown measurement, the samples are taken apart and then put back together so that a different part of the wire was used each time as the plate of the capacitor. In addition, by changing the force on the screws the separation between the plates of the capacitor was changed.

A measurement of the potential drop across the resistor versus applied voltage is made, for each different spacing, so that the current through the capacitor versus applied voltage is determined. An example of such a measurement is given in Fig. 5. The value of applied voltage at which the current through the resistor becomes nonlinear is chosen to be the value of the breakdown voltage.

The results from the capacitance measurement reflect an average separation between the two substrates used. This is due to the fact that for separations larger than 500 nm the capacitance is not dominated by the capacitance of the two crossings. Various parts of the metallic lines contribute in significant measure to the total value of the capacitance. With that in mind, we have estimated the possible deviations of the two separations at the two crossings, with respect to the average separation.

We estimate these deviations for a variety of possible geometries of the substrates and uncertainties due to photolithography and alignment. The geometries considered are the two substrates having positive and negative curvatures. We tried all combinations of putting together two substrates with different curvatures. We also considered the possibility of the two substrates being put together with a relative angle. We assigned the uncertainty as the limits of the typical range of separations; these are represented in Fig. 6 as relative error bars.

Finally, we note that uncertainties of this type seem unavoidable in planar geometries since, as mentioned before, the value of the capacitance of the leads plays an important role as the capacitance of the crossings, down to very small separations.

Nominally, the use of very flat substrates would give us better control of the separation between the two substrates. However, in such a case a measurement of different separations using the same electrodes would become very difficult, as a very precise mechanism would be needed in order to change their distance. The fact that the substrates are not perfectly flat affords us the possibility of tuning the distance between them by using the application of a force.

No attempts were made to control the humidity, temperature, or composition of the air in the room, during this experiment.

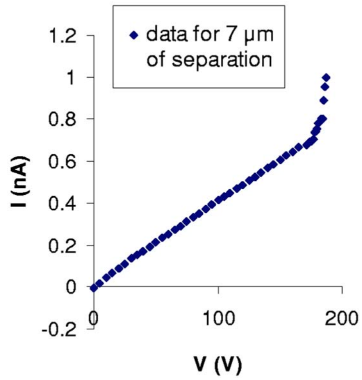


FIG. 5. Current through the 10 MΩ resistor in series with the capacitor, as a function of the applied voltage from the dc voltage source. The value of the electrode separation is 7 $\mu$m. For this value of separation, the value of the breakdown voltage is taken to be 185 V. The linear part of the curve is due to a leakage of approximately $2.5\times10^{11}$ Ω.

## V. RESULTS AND DISCUSSION

We used the method described above to measure the breakdown voltage of air, in atmospheric pressure, for sepa-

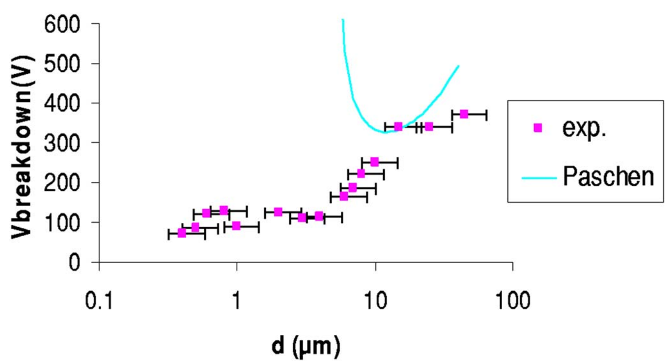


FIG. 6. Data for breakdown voltage of air as a function of electrode separation. The error bars represent the statistical uncertainty due to geometrical factors (see text). The solid line is Paschen's curve. For spacings below 10 $\mu$m the data do not approach Paschen's curve.

rations of the electrodes ranging from 400 nm to 45 $\mu$m. Before taking the data, we measured the breakdown voltage at 4 $\mu$m of separation four times. The results were within 10% of each other. We then took data for each different separation once. The results are shown in Fig. 6. The theoretical prediction for the value of breakdown voltage in air is based on an avalanche effect of electrons being accelerated by the electric field and ionizing, through collisions, air molecules. This mechanism is described by Townsend electron avalanche theory and is represented by what is known as Paschen's curve (solid line in Fig. 6).

It is obvious that the data do not follow Paschen's curve for electrode separations below 10 $\mu$m. The analysis of the data for separations below 10 $\mu$m will be given in a subsequent publication. The data above 10 $\mu$m approach Paschen's curve, even though they do not lie entirely on it. This is not surprising, since the shape of Paschen's curve depends on parameters, e.g., humidity, that are not controlled by the experiment. Also, the number of data points in this regime is very limited. Finally, it is common in the literature that the data points near the minimum of the curve approach it, but do not lie entirely on it.

In conclusion, we have developed a new method for measuring the breakdown voltage in air, for electrode separations of 400 nm to 45 $\mu$m. Our method enables us to monitor the actual value of the separation before each measurement. It also approaches the geometry of an idealized parallel plate capacitor, because of its very large aspect ratio ($80\times 80\ \mu\mathrm{m}^2$ electrodes separated by as little as 400 nm) and because of the small surface roughness (average of 6 nm). Finally, as shown before, the values of the breakdown voltage are very different from Paschen's curve for small separations of the electrodes.

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