Focused Ion Beam Milled Sub-Micron Capacitive Gaps in Coplanar Transmission Lines

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Abstract: By milling sub-micron wide air gaps with a focused ion beam (FIB) into coplanar waveguide (CPW) transmission lines, it was demonstrated that a FIB can be an effective tool for micro- and mm-wave device fabrication. The milled gaps, with widths of about 70 nm, were cut across the center conductor of the CPW lines, as well as across shunt line connections. Straight cuts and angle cuts were investigated. Capacitances of 8.5 to 12 fF were extracted from the equivalent circuit models and possess nearly ideal thin-film capacitor topology due to the absence of significant inductive effects. The devices were measured and characterized from 1 to 65 GHz. The effects of gallium contamination during milling were also taken into account in the circuit model.

Introduction

In the last few years, there has been an increase in the use of focused ion beam (FIB) milling for micro and nano structure fabrication. This is mainly due to the FIB’s ability to mill material with high precision, high-aspect-ratio structures with relatively smooth sidewalls without the use of a mask. Devices such as microfabricated accelerometers [1], BSCCO stacked junctions [2], microgratings for integrated optics [3], and micromilled trenches [4] have already been demonstrated.

The milling capabilities of a FIB system have been utilized in this paper to demonstrate that this tool can effectively be used to fabricate nearly ideal micro- and mm-wave planar capacitors by cutting sub-micron wide gaps across the conductors of coplanar waveguide (CPW) transmission lines. Even though FIB milling is not a very suitable process for high-volume manufacturing, since one device can only be fabricated at a time due to the direct write approach, this technique does have the advantage of producing devices where high yield and great precision is needed, such as for military or space applications. Also, FIB milled capacitors have the advantage over their metal-insulator-metal (MIM) counterparts that they can be processed without the need of a dielectric layer to produce low value capacitors. They also have the benefit over MIM and interdigital capacitors in that they can be fabricated with a single layer process without the need masking and corrosive etching steps and use up much less real state due to their extremely narrow milled area.

This investigation is also part of a larger study on the potential use of nano-fabricated capacitive gaps in micro-electro-mechanical-systems (MEMS) devices. By applying the fabrication technique to suspended structures, MEMS structures such as switches and varactors can be fabricated for applications in the high mm-wave frequency band. The ability to produce angle-cuts, which result in overlapping metal sections, can also find use in microwave frequency switches.
**FIB Milling Process**

Milling with a FIB system is achieved by focusing a beam of ions down to a submicron area. This beam is accelerated to a high voltage, generally between 5 and 50 KeV, and interacts in a well-defined area within the target material. The ion beam is produced from the field ionization of a gallium metal that is coated on a needle tip, usually made of tungsten or platinum, with a radius in the sub micron range. The ionized field (>10^8 V/cm) is created by a high electric field at the needle tip. The ion beam can then be focused to a beam diameter ranging from less than 5 nm up to half a micron by changing the beam current density. This is accomplished by controlling the strength of the electrostatic lenses and adjusting the effective aperture sizes [5]. And since FIB milling is generally a sputtering process, undesired Ga ion implementation into the sample substrate can also occur [5, 6]. Material removal in the focused area can be precisely controlled and viewed since the accelerated ions will generate secondary electrons and ions which can be detected much in the same way as in a scanning electron microscope system. Exact etch patterns and depths can be specified in many computer controlled FIB systems.

**Fabrication Process**

All devices were fabricated on 400 mm-thick, high-resistivity silicon wafers ( > 2000 Ohm-cm). Fig. 1 shows the layout of the CPW line with the FIB milled gap. Two types of cuts were analyzed: a straight cut and a milled device with the ion beam set at a 52˚ angle with respect to the straight cut (see Fig. 2).

![Fig. 1. Layout drawing of FIB milled CPW line (S=45 µm, W=27 µm) and SEM of milled gap in CPW center conductor.](image)

The metal lines consisted of a 0.4 mm thick chromium/gold layer fabricated using electron beam deposition. After the CPW transmission line deposition, a 0.2 mm thick polymethyl methacrylate (PMMA) layer was spun onto the sample and cured. This was done so a conductive coating (50 Å of Cr) can be applied to the sample that is needed to eliminate electron charging during the FIB milling process. A cross sectional view of the cut through the layers is shown in Fig. 2.

The CPW lines were milled using the FEI DB235 dual beam FIB system. A 30 keV ion beam was used with a set current of 10 pA to mill the gaps. The etch depth was set to 0.6 mm, corresponding to the total metal and PMMA layer thickness. This corresponds to an etch time of about 3 minutes for the straight cut. For the angled cut, an etch depth of 0.9 mm was selected which took about 5 minutes to complete. The straight and angle cuts were made slightly longer then the 45 mm wide center conductor to ensure a
complete cut over the entire width. After milling, the Cr and PMMA layers were removed by placing the sample in a heated (80º C) Microposit 1165 photoresist stripper. A SEM of the top view of a milled gap is shown Fig. 1.

![Focused Ion Beam](image1.png)

Fig. 2. Cross sectional view of FIB cut into sample surface. (a) shows straight cut and (b) shows the cut at a 52° angle (not drawn to scale).

**Measured and Modeled Results**

Series gaps in a CPW center conductor have already been modeled using a lumped Pi-network consisting of a series capacitor and two fringing capacitors [7]. For this application, a series inductor/capacitor in parallel with a resistor model was used. The parallel resistor (Rg) was needed to account for the conductive effects caused by the ion beam milling, as already mentioned. The series resistor (Rs) was used to model parasitic resistive effects in the circuit before and after the milled gap. Model extraction from the measured data was performed using Agilent ADS [8]. CPW transmission line models were added to include the effects of any transmission lengths not de-embedded during calibration. Fig. 3 shows a schematic of the circuit model. Measurements were performed from 1 to 65 GHz on a Karl Suss probe station with a Wiltron 360 vector network analyzer (VNA). 150 µm pitch 3 prong probes were used to measure the devices and the TRL on wafer calibration standards.

<table>
<thead>
<tr>
<th>Type</th>
<th>C (fF)</th>
<th>Rg (kΩ)</th>
<th>Rs (kΩ)</th>
<th>L (pH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight</td>
<td>8.5</td>
<td>25</td>
<td>11.2</td>
<td>0</td>
</tr>
<tr>
<td>Angle</td>
<td>12.0</td>
<td>25</td>
<td>10.8</td>
<td>0</td>
</tr>
</tbody>
</table>

![EXTRACTED EQUIVALENT CIRCUIT VALUES](image2.png)

Fig. 3. Equivalent circuit model for FIB milled capacitor and table of extracted values.

Fig. 3 also displays a table of the extracted equivalent circuit values while Fig. 4 shows the measured to modeled comparison for both type of devices tested (S11 and S21 magnitude and phase). Capacitance values of 8.5 and 12 pF were extracted for the straight and angle cut devices, respectively. The bigger capacitance value for the angle cut was expected due to larger surface area of the cut sidewalls. The values extracted for parallel resistor, Rg, clearly shows there is some conductive effect across the gap in all the tested cases. This seems to validate the undesired effect of gallium contamination of the substrate during the ion beam milling process. This unwanted effect is most evident in the S21 plots below 5 GHz.
Fig. 4. Measured (straight lines) and modeled (lines with markers) comparisons showing magnitude (left axis) and phase (right axis) plots.

Conclusion

It has been demonstrated that a FIB tool can be effectively used to fabricate high precision micro- and mm- wave devices with sub-micron feature sizes. FIB milled capacitors with virtually ideal characteristics have been fabricated using FIB milling. Lumped element values for the capacitances and parasitic values were derived from an equivalent circuit model. Besides undesired gallium doping, these capacitors showed negligible parasitics at high frequencies.

References