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Miniaturized microcantilever-based RF microwave probes using MEMS technologies

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Abstract

In this study, miniaturized microwave cantilever-based probes - using silicon-on-insulator (SOI) technology - are proposed for the on-chip electrical characterization of nanodevices. In contrast with conventional on-wafer probing structures, small pad dimensions around $1 \mu\text{m}^2$ associated with a $4.5 \mu\text{m}$ -pitch are demonstrated. The probe structure, designed in coplanar technology, is optimized in order to ensure a low contact resistance. The fabrication steps of the probe structures have been developed by means of microelectromechanical systems (MEMS) technology. Measurement performance up to 50 GHz exhibit return loss better than -15 dB and insertion loss lower than -2.5 dB.

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Keywords: HF probes; MEMS; SOI technology; on-chip nanocharacterization

1. Introduction

The future of nanoelectronics will depend on our ability to measure accurately the electrical characteristics of nanodevices in a wide frequency spectrum. In particular, the electrical measurements of attofarad capacitances, nanotubes, nanowires are well-known challenges. To address these challenges, dedicated on-wafer probing structures with probing dimensions in the order of the micro- or nanometer size must be developed. For many years, the scientific community has been using conventional ground-signal-ground (GSG) probes for the characterization of

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high-frequency (HF) integrated devices [1]-[2]. Using such probes, the characterization of devices in the GHz-THz range has been successfully achieved [3]- [4]. However, in general this kind of probes exhibit contact areas in the order of hundreds of μm^2 ($> 10 \times 10 \mu\text{m}^2$) and pitch (spacing between contacts) dimensions in the order of tens of micrometers ($> 30 \mu\text{m}$). Furthermore, with these critical dimensions we need on-wafer test pad areas to be around at least $50 \times 50 \mu\text{m}^2$ to make sure an optimal electrical contact is achieved [5]. Moreover, the resulting tip stray-capacitance is in the order of few fF. In general, such dimensions involve resistance, capacitance and inductance parasitic effects that can be most important in the HF characterization of electronic nanoscale components. Recently, miniaturized probes have been developed for the range 500 GHz-750 GHz [6]. These probes show a contact area around $40 \times 10 \mu\text{m}^2$ with a pitch in the order of $30 \mu\text{m}$. However, despite this reduction of the sizes of the pads and the pitch, these probes are still not compatible with the dimension brought into play in nanoelectronic devices. In addition, the relatively complex fabrication process of these commercial HF probes makes their market price relatively high.

Therefore, the major challenge of this work is to develop a new type of probing structures to meet the specific needs of microwave characterization at the nanoscale. In particular, a reduction of the contact pad area of three orders of magnitude, compared to existing commercial HF probes, is considered to diminish significantly parasitic effects. Consequently, the availability of micrometric probes will result in a reduction of the access pad size and therefore a significant increase of the on-wafer device integration. The proposed probe structure takes fully advantage of the SOI technology. In particular the mechanical properties of silicon and the possibility to use metals like gold and nickel have been exploited. Actually, the silicon cantilevers possess a good elastic deformation property and the tips in the gold and nickel imply a low contact resistance between the probe tips and the device under test (DUT) pads.

2. Structure design and Fabrication

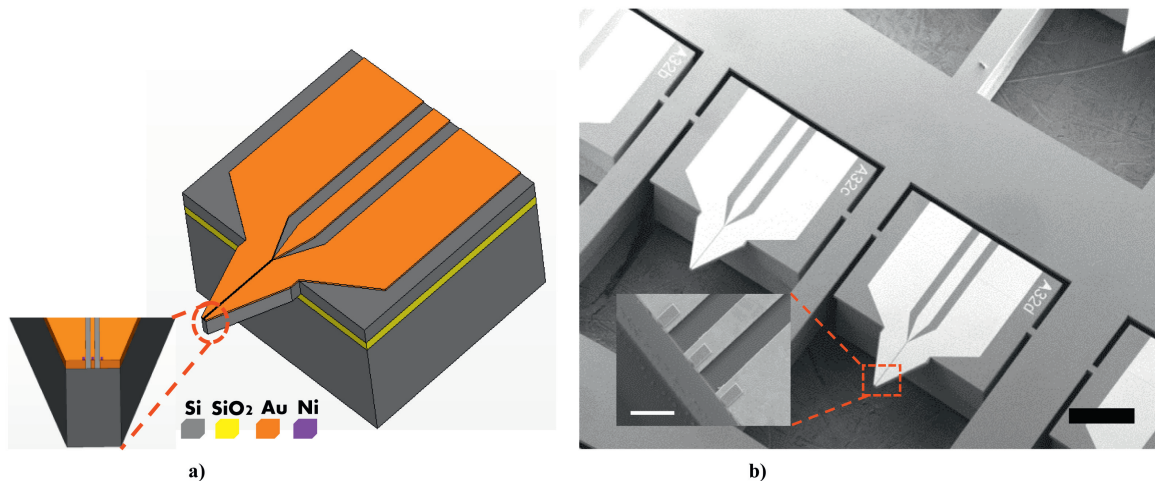


Fig. 1. (a) Miniaturized RF probe cross-sectional view. (b) SEM image of the fabricated probes - scale bar = $500 \mu\text{m}$. Inset shows zoom of probe tip with Nickel pads - scale bar = $4 \mu\text{m}$

The study presented here is an extension of our previous work in the field, dedicated to the micromechanical and electromagnetic modeling of such miniaturized MEMS-based HF probes [7]. The design and optimization of the probes are based on mechanical ($\text{\textcircled{R}}\text{COMSOL}$) and electromagnetic ($\text{\textcircled{R}}\text{CST}$) FEM modeling. The probe must provide enough mechanical deformation to allow good physical contact between the probe contacts and the DUT pads. Additionally, the probe structure must deliver enough force to generate the lowest possible contact resistance

between the probe tips and the DUT pads. The probe material should provide excellent elastic properties with high yield strength to avoid damage to the probe – and indeed the DUT surface. Silicon presents high yield strength in the order of 4.5 GPa [7]. The mechanical stress analysis of our probe structure shows that the maximum mechanical stress is around 89.7 MPa under a load of 2 mN per probe tip and this maximum is located at the base of the cantilever [7]. Given that the rupture limit of silicon is reached at around 4.5 GPa, this gives a large safety margin during the probe manipulation and in case of possible user error. We have used evaporated nickel for the tip contacts due to the high hardness and good electrical properties which should increase tip robustness and give a low contact resistance. The load of a contact force of 2 mN per probe tip induced a tip displacement of 1.74 μm . This displacement and deformation of the thinner silicon material provide a maximal contact area induced by the cantilever deflection when the cantilever tips press on the pads of the DUT. As reported [8], having a flat contact surface and an appropriate force between two metals allows a lower contact resistance due to the cold welding of metals. Consequently, an optimal electrical contact between the probe and the device under test (DUT) pads will be ensured. The probe is designed in coplanar transmission line geometry as shown in Figure 1(a). Thus, from an electromagnetic point of view, a tapered coplanar line topology (gold lines deposited onto SOI substrate are optimized to achieve a 2 μm -width signal line associated with a 2.5 μm -gap [7]. The cantilever is designed using 15 μm thick DL (device layer) on high-resistivity SOI substrate (1000 $\Omega\text{ cm}$). Several cantilever have been fabricated whose dimensions are: base width (w) = 300 μm and lengths (L_c) = 100, 200 and 400 μm . The probe pitch is 4.5 μm with four contact areas =1, 2, 4 and 10 μm^2 . The probe, based on MEMS technology, are realized by using IEMN fabrication facilities. The SEM image in Figure 1(b) shows the side view of the fabricated probe structure as well as tips contact based on Nickel in the inset.

3. High-frequency Measurements

Several probes structures including different design parameters have been fabricated. In particular, dedicated structures that associate two back-to-back probes have been achieved in order to measure probe microwave performance. Actually, this configuration allows a fast and simple way to perform a RF characterization of the probes. Thus, thanks to this structure preliminary characterization of the probe can be conducted directly on the wafer without the need of the integration of the probe onto a PCB (printed circuit board) for example. The RF measurements were made with a vector network analyzer (N5245A Agilent Technologies) and two GSG commercial RF probes (SUSS MicroTec) as shown in Figure.2. The return loss and insertion loss measured according to the configuration given in Figure 2 are presented in Figure 3 for three different structures (variation of the cantilever length: 100, 200 and 400 μm).

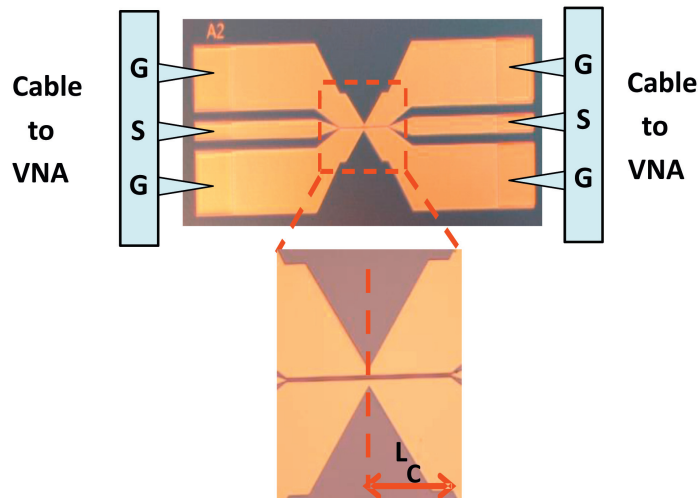


Fig. 2. On-substrate photograph of the probing structure that associate two probes, including the high-frequency testing procedure.

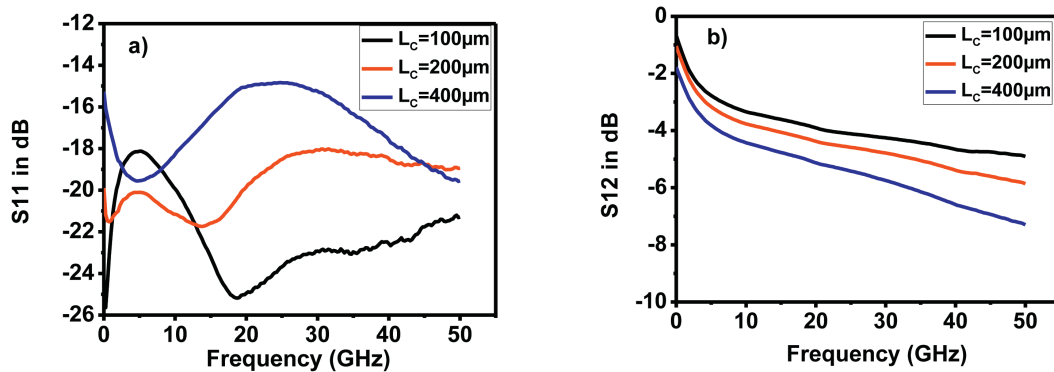


Fig. 3. RF characterization of the probe structure that associate two probes. (a) Measured return loss and (b) insertion loss.

One can note that the return loss is better than -15 dB in the frequency range of interest and that the insertion loss is in the order of -2.5 dB at 50 GHz for a cantilever length of 100 μm (for a single probe half of the value reported in Fig 3.b). The data demonstrate state-of-art performance for miniaturized GSG probes having micrometer dimensions - complementary mechanical and electrical HF characterizations are currently in progress.

4. Conclusion

This article describes a novel prototyping of miniaturized microcantilever-based RF microwave probes. The probes have been developed by using microelectromechanical systems (MEMS) technology on SOI wafers. The probe fabrication with a pitch of 4.5 μm associated with a small pad dimensions - around $1\mu\text{m}^2$ - has been achieved. The preliminary measurements data of the proposed miniaturized probe show that the probe is suitable for the high-frequency characterization of integrated nanoscale devices.

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