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Branchline and directional THz coupler based on PECVD SiN_x-technology

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***Abstract*— A fabrication technology to realize THz microstrip lines and passive circuit components is developed and tested making use of a plasma-enhanced chemical vapor deposition grown silicon nitride (PECVD SiN_x) dielectric membrane. We use 2 µm thick SiN_x and 300 nm thick gold layers on sapphire substrates. We fabricate a set of structures for thru-reflect-line (TRL) calibration, with the reflection standard implemented as a short through the via. We find losses of 9.5 dB/mm at 300 GHz for a 50 Ohm line. For a branchline coupler we measure 2.5 dB insertion loss, 1 dB amplitude imbalance and 21 dB isolation. Good control over the THz lines parameters is proven by similar performance of a set of 5 structures. The directional couplers show -14 dB transmission to the coupled port, -24 dB to the isolated port and –25 dB in reflection. The SiN_x membrane, used as a dielectric, is compatible with atomic force microscopy (AFM) cantilevers allowing the application of this technology to the development of a THz near-field microscope.**

So far the well-established approach in THz circuits development is to use rectangular metal waveguides for the main circuitry in combination with printed microstrip circuits on electrically thin substrates for active components. In order to ensure continuous ground these microstrips are suspended in a metal channel attached to the waveguide. This has great advantages, for example low losses and intrinsic high-pass filtering of the waveguides. However, for some applications it is favorable to avoid a bulky waveguide approach. Moreover, micromachining of waveguide blocks requires highly specific equipment and the fabrication process cannot be scaled easily to large quantities. Hence, much effort is being put into the development of on-chip THz circuitry, exploring CPW [1], microstrip [2], and slot-lines [3] as the main transmission line. At THz-frequencies these structures are often difficult to realize because they require extremely thin substrates or membranes of very high uniformity. For the GHz range silicon nitride (SiN_x) has proven itself particularly useful as a membrane material, enabling for example advanced techniques as the GHz near-field impedance microscope [4], which provides new insight into various fields in condensed matter physics [5, 6]. The unique mechanical and chemical properties of SiN_x, and its compatibility with a large variety of materials make this material very attractive in THz applications.

Here we present microstrip transmission lines suitable for THz on-chip circuitry based on PECVD SiN_x as a dielectric. We believe it can find applications in various fields including on-chip THz circuitry, such as integrated THz transceivers [7].

We have chosen microstrips as a transmission line topology because it allows minimizing the interaction with the background through the shielding ground plane, giving immunity to the topography cross-talk known for AFM systems. The microstrip allows also increasing the field amplitude due to the confinement of the signal power in the small gap between the tip and the shield. Our study is organized as follows. First, we fabricate a TRL [8] standard set, including Thru, Reflect and Line devices, with Reflect implemented as a short circuited Thru. Secondly, we use a landing probe setup with a VNA and extension modules for characterization of the THz performance. Thirdly, based on the basic characteristics of our microstrips we design and measure branchline and directional couplers, and we compare the results to simulations.

The performance of the devices is evaluated with a dedicated setup in the 220 to 325 GHz range with waveguide probes coupled to the thin-film circuit. The setup uses Keysight PNA-X with OML extension modules working in the WR-3 waveguide band equipped with 325B-GSG-75-BT probes from GGB Industries (Figure 1, a). These probes provide reliable mechanical and electrical contact through the landing of three spring contacts serving as ground-signal-ground (G-S-G) for the CPW configuration. In order to avoid unnecessary impedance mismatch we designed the corresponding contact pads as a segment of a 50 Ohm CPW line with dimensions of 50 µm for the S-contact width, separated by 25 µm from the G-contacts. For a smooth transition to the dimensions of the microstrip (2.5 µm) we taper the CPW over a distance of 100 µm. The CPW ground stripes merge into a single ground layer of a 12.5 µm long microstrip. Contact pads, tapered CPW and microstrip segment together form a fixture, indicated with a dashed

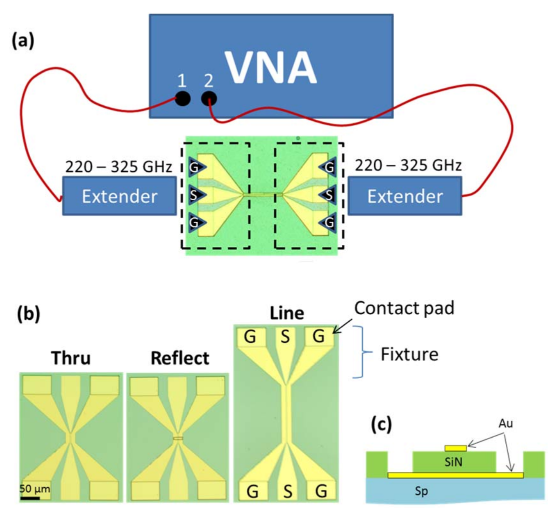

Fig. 1. (a) Measurement setup for two-port electrical characterization with landing probes in ground-signal-ground configuration (G-S-G). Dashed boxes indicate the fixtures. (b) Photographs of the TRL (Thru, Reflect, Line) calibration set. (c) Layers stack: sapphire, Au, SiN_x, Au.

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rectangle in Fig. 1a. We point out that although these fixtures are natural parts of each device they need to be considered as parts of the measurement setup. Therefore, we apply a TRL de-embedding procedure, thus allowing to properly set the measurement reference planes directly at the center of the Thru standard and eventually enabling the direct measurements of microstrip components placed between those planes. We design the three TRL structures (Fig. 1b) as follows. The Thru connects directly two fixtures, the Reflect shorts each fixture at their interface and the Line connects two fixtures with a 125 µm long microstrip.

All devices are fabricated on a single 350 µm thick c-cut sapphire wafer (Fig. 1c). First, the ground layer of 300 nm thick e-beam evaporated gold (yellow) is deposited with 5 nm Ti as an adhesion layer. We pattern the G-electrodes of the fixtures in the ground layer using a standard PMMA lift-off technique. In the second step, the 2 µm PE-CVD low stress silicon nitride layer is grown at 300°C using an Oxford Instruments PlasmaPro 80, with a growth rate of 12.5 nm/min. To uncover the contact pads for probe-landing and the *via* for the reflection standard we etch through the SiN_x layer using an SF6 plasma in a reactive ion etching system. Finally the microstrips and signal conductors of the CPW fixtures are patterned. For this another 300 nm Ti-Au layer is deposited followed by a standard PMMA lift-off process.

The measured 55 Ω microstrip lines present losses of 9.5 dB/mm and an effective permittivity of 7.5. A 3-D HFSS simulation gives results that correspond well to the measurements if a value of 6.5 is used for the permittivity of SiN_x, compared to 7 in bulk stoichiometric Si_3N_4. The losses are very well described by the resistive loss in gold. Therefore we assume the dielectric loss to be negligible.

To test the performance of more complex circuits fabricated with this technique we design a branchline coupler and directional coupler representing two key components of real THz devices. To fully characterize these 4-port structures with the 2 port setup we fabricate each structure in 3 layouts, with fixtures attached to the pairs of ports 1:2, 1:3 and 1:4. Idle ports are loaded with 2-mm long microstrip lines compacted into a meander shape. Even though the loads are terminated with open circuits, the estimated reflection from the load is less than -36 dB due to the high loss in the line. The branchline coupler in 1:4 configuration is shown in figure 3a with ports indicated with circled numbers, microstrip ground (G) and stripline (S) indicated with arrows. It is designed to be slightly overcoupled to extend the usable frequency range, with 55 Ohm main line impedance and 35 Ohm low impedance branches. The de-embedded measurement results are compared with simulations in Fig. 3b. We obtain transmission of -5÷-7 dB for the S21 and -5÷-6 dB for the S31. The 1 dB amplitude imbalance range is 230 to 305 GHz (27% bandwidth). The best isolation of -21 dB between ports 1 and 4 is achieved in the frequency range of 270 to 280 GHz. The measured data nicely correspond to simulations based on material parameters extracted from the TRL measurements. The directional coupler uses a pair of microstrips coupled through a 1 µm gap over a distance of 125 µm. It shows -14 dB transmission to the coupled port, -24 dB to the isolated port and -25 dB reflection.

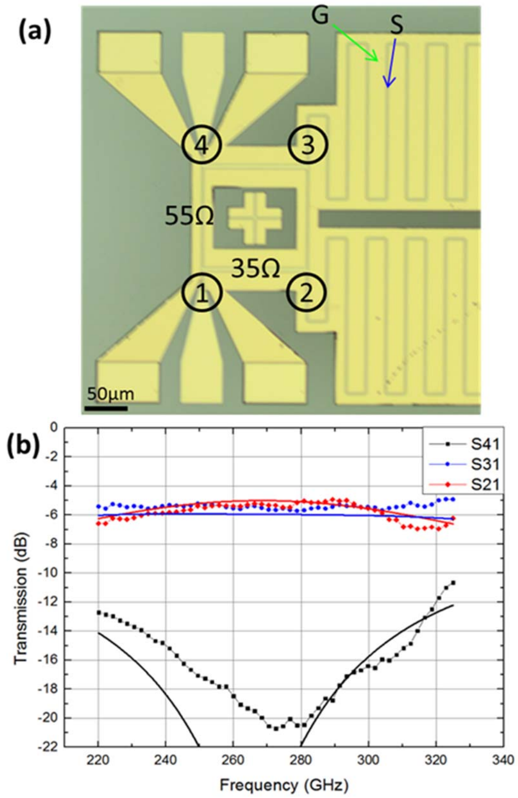

Fig. 2. (a) Photograph of a branchline coupler in 1:4 configuration. Ports are denoted with numbers 1-4, G and S denote ground and signal electrodes of the microstrip. (b) Performance of the branchline coupler measured for three different fixture layouts (symbols). Lines are the results of the simulations.

To conclude, a branchline and a directional coupler were designed, fabricated and characterized yielding high performance and good correspondence to simulations.

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