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A New Fabrication Process for Low-Loss Millimeter-Wave Transmission Lines on Silicon

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1. Introduction

During the past several decades, Si-based technologies have made great progress and have brought about the advent of sub-quartermicron featured ULSIs. The application of such Si-microfabrication technologies has recently been expanding to other areas such as rf electronics and sensory electronics and the technologies are expected to combine the rf devices and the sensors with ULSIs on a chip because of their fully-matured and low-cost fabrication processes.[1] Si-microfabrication technologies have also been applied to Si-based millimeter-wave monolithic and/or hybrid integrated circuits and systems.[2-4] The key issue in the application of Si-based millimeter-wave transmission lines is the reduction of dielectric loss due to Si substrates as well as the reduction of conductor loss due to interconnections. Some processes have been developed to overcome the high-dielectric loss problem, however, these processes are neither necessarily compatible with ULSI-fabrication processes nor are they practical in their use of the so-called backside process.[2] To achieve low-loss millimeter-wave transmission lines, we have developed a new fabrication process consisting of thick polyimide film processes, electroplating, and chemical mechanical planarization (CMP). The goal of this work is to fabricate the low-loss millimeter-wave transmission lines as coplanar waveguides (CPWs) with deep V-shaped grooves to reduce the dielectric loss and with thick metallization to reduce the conductor loss (Fig. 1). The CPWs ensure extremely low loss and dispersionless characteristics at >100-GHz regime. In addition, the air-bridge wiring is also demonstrated by using this technology for multi-level interconnection.

2. Design and Fabrication Processes

The transmission lines were designed based on three-dimensional electromagnetic simulation. The effects of the dielectric resistivity, metal thickness, and groove depth and shape have been taken into account to achieve 50-Ω impedance and low loss over a 100-GHz bandwidth. The CPWs with thick metallization especially need strictly-controlled tall sidewalls to confine the electric field in the air between the conductor sidewalls. To realize such CPWs, we have developed a new fabrication process. The transmission lines were fabricated on 6-inch-diameter 625-μm-thick Si (100) substrates with 1-kΩcm resistivity. Figure 2 shows the fabrication processes: (a) The V-groove structures were made to a depth of 10 μm with an SiO_2 mask by an anisotropic etching in a KOH solution. (b) The polyimide was spin-coated after removal of the SiO_2 mask. CMP was performed to keep the polyimide as sacrificial films in the grooves for the metallization. A 2-step CMP was performed to remove a 1.0-μm-thick polyimide layer: First, the polyimide was roughly polished using 1.0-μm-diameter alumina slurry and then it was finely polished using 0.3-μm-diameter alumina slurry, both in basic suspensions. (c) A 200-nm-thick Au/Cr layer was deposited by electron-beam (EB) evaporation as a seed layer for Au electroplating. A conventional resist was then coated and patterned by lithography. (d) Typically, 10-μm-thick Au film was selectively electroplated on the EB-evaporated Au layer. CPWs are strictly defined since the lateral growth of Au is prohibited by the resist wall. (e) After the resist and the seed layer were removed by wet etching, the polyimide sacrificial layer was ashed in oxygen plasma. Finally, we were able to obtain a CPW having tall and precipice sidewalls with V-grooves as shown in Fig. 3(a). Furthermore, by repeating these processes, a CPW with an air-bridge structure was fabricated as well (Fig. 3(b)).

3. Performance of Transmission Lines

All the fabricated CPWs exhibited a return loss (S11) of less than -20 dB when measured up to 40 GHz with a network analyzer which ensures the 50-Ω characteristic impedance. Figure 4 shows the loss characteristics (S21) measured with the network analyzer for the conventional CPW with S (signal line width) = 12 μm, W (signal-ground spacing) = 20 μm, and t (thickness) = 3.5 μm, and the sidewall CPW (no groove) with S = 29 μm, W = 16 μm, and t = 10 μm. Since the conductor loss is dominant at frequencies below 100 GHz, the sidewall CPW with thicker metallization exhibits better performance. When the frequency exceeds 100 GHz, the dielectric loss of the substrate affects the CPW performance. To examine the >100-GHz characteristics of the CPWs, time-domain measurements have been conducted using an electro-optic sampling (EOS) technique.[5] Electrical pulse signals with a 2.8-ps FWHM, which corresponds to a 3-dB bandwidth more than 100 GHz, are launched onto the CPWs with a high speed photodiode bonded to one end of the CPWs. The photodiode is illuminated by 500-fs-width optical pulses generated from an ultrashort pulse laser. Figure 5 shows the waveforms of these electrical pulses measured at 0.5-mm and 1-mm distances from the launched point for the sidewall CPWs with and without 10-μm deep grooves. For sidewall CPW with the grooves, the amplitude decrease is as small as 5 % and the electrical pulses maintain almost the same waveform after 0.5-mm propagation. Without the grooves, on the other hand, the amplitude decrease is over 20 % and the pulse is slightly broadened. In addition, the propagation delays are respectively 3.4 and 4.1 ps for CPWs with and without the grooves, meaning that the groove decreases the substrate effect as expected. These experimental characteristics confirm the effectiveness of the sidewall CPW with a groove structure as a transmission line for millimeter-wave applications.

4. Summary

We have developed a new Si-micromachining technology to fabricate high-performance transmission lines for application to millimeter-wave circuits and systems and have successfully tested the lines at frequencies over 100 GHz. This fabrication technique paves the way for the fusion of millimeter-wave systems and ULSIs on a chip.

Acknowledgments

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References

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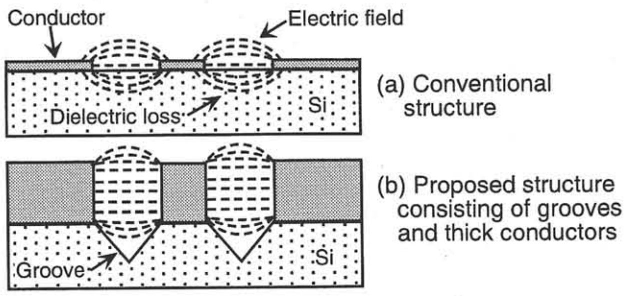

Fig. 1 Schematic cross section of CPW on Si.

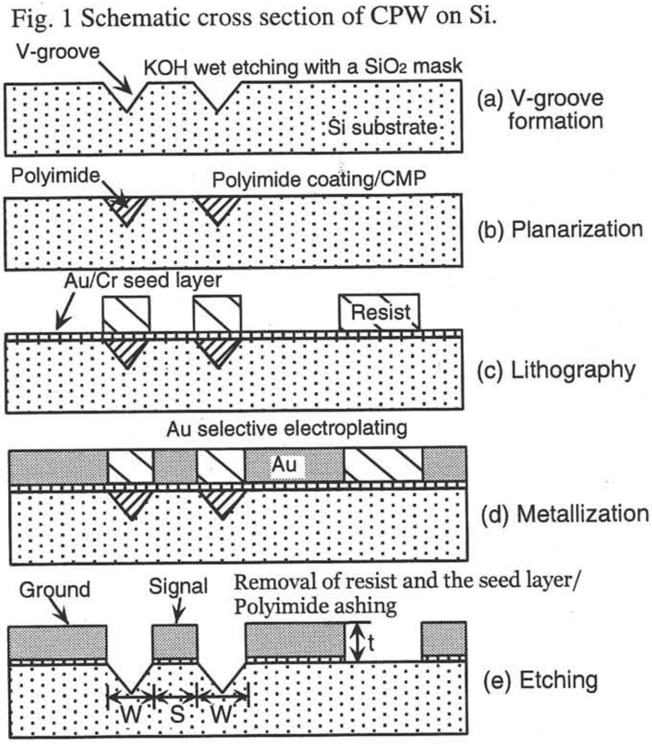

Fig. 2 Schematic drawing of the fabrication processes.

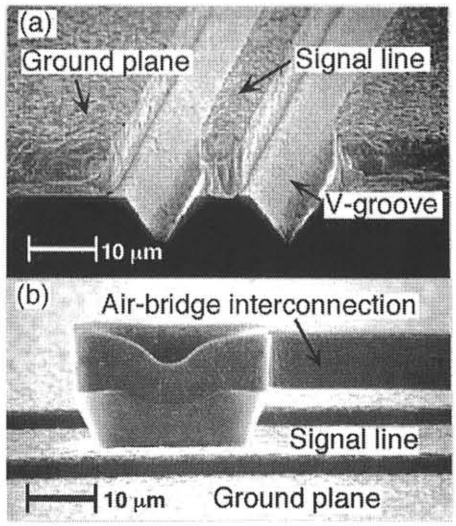

Fig. 3 Pictures of transmission lines with (a) V-grooves and (b) air-bridge interconnection.

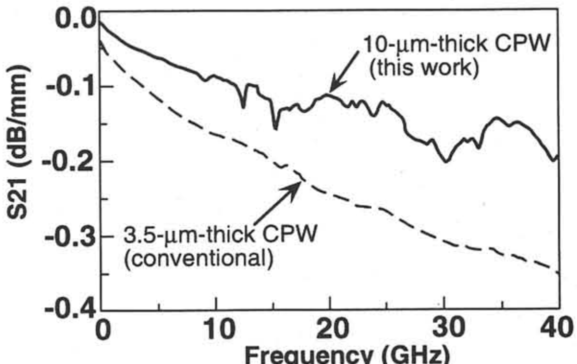

Fig. 4 Comparison of the loss characteristics between thin and thick CPWs.

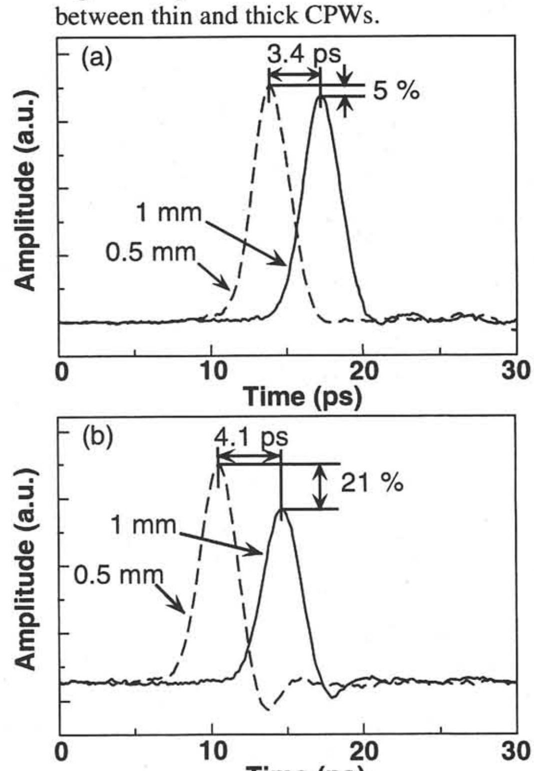

Fig. 5 Time domain waveforms measured at different propagation distances (a) with and (b) without grooves.