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RF model of flexible microwave switches employing single-crystal silicon nanomembranes on a plastic substrate

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ABSTRACT

This paper reports the realization and radio frequency (RF) modeling of flexible microwave switches (as a simple circuit example) employing single-crystal silicon nanomembranes (SiNMs) on plastic substrates. High-energy, high-dose ion implantation and high-temperature annealing are performed before the nanomembrane release and transfer process, enabling good high-frequency response of the flexible switches. RF/microwave models of the microwave single-crystal SiNM switches on plastic substrate are developed. The model shows good agreement with the experimental results with different switch areas and under different operation conditions. The factors that are most influential with respect to flexible switch characteristics are revealed. The study demonstrates that single-crystal SiNM microwave switches can be fabricated and accurately modeled for high-performance, flexible, monolithic microwave integrated systems.

1. Introduction

High-performance, flexible electronics have become increasingly attractive in recent years because of their unique advantages such as bendability, better mechanical properties, light weight, and the ability to conform to the shapes of any surface [1]. Materials such as organic semiconductors, amorphous silicon and polycrystalline silicon are widely used in flexible electronics. Although there is a considerable amount of research focused on improving these kinds of flexible electronics [2–7], fundamental limitation exists for these materials. The carrier mobilities of these materials are significantly lower than those of inorganic, single-crystal semiconductor materials. Consequently, flexible electronics based on organic semiconductors, amorphous silicon and polycrystalline silicon are limited to low- or moderate-speed applications such as electronic papers, electronic textiles, and flexible displays [1–7].

Device speed is one of the most important factors in flexible electronics. Higher device speed can greatly enhance data transfer, power gain, and power consumption. Fast and flexible electronics are highly desired for a variety of applications, e.g., RFIDs, personal wireless devices, rollable airborne/space-borne communication systems, and surveillance and remote sensing radars [1]. High-speed flexible electronics require semiconductor materials with high carrier mobilities. Single-crystal silicon is an attractive candidate because of its low cost, high mobility, suitability for large-scale integration and compatibility with current industry semiconductor fabrication facilities. Flexible devices employing single-crystal Si nanomembrane (SiNM) transistors became a reality in 2004 [8], with the development of transfer techniques based on silicon-on-insulator (SOI) wafers. In particular, the high carrier mobility of SiNMs makes them promising for high-frequency applications [9–11].

We have developed a unique, combined high-temperature and low-temperature process for transferrable SiNMs to transform the superior carrier transport characteristics of SiNMs into a series of high-speed flexible devices, e.g., thin-film transistors (TFTs), diodes, photodetectors and passive components [12–18]. To build the flexible, monolithic microwave integrated systems, flexible circuits that can be operated at RF/microwave frequency are necessary. Moreover, to accurately and efficiently design flexible microwave integrated circuits, an RF/microwave circuit model is essential. An equivalent circuit model can be used for a design to deliver sufficiently accurate performance at the device or circuit level, with much less computation time than a physical model [19,20]. In this paper, we successfully fabricated flexible microwave single-pole single-throw (SPST) switches (as a simple circuit example) employing single-crystal SiNMs on a plastic substrate.

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Additionally, an RF/microwave equivalent circuit model is developed for these microwave switches. The model provides guidelines for designing and using microwave switches in flexible, monolithic microwave integrated circuits (MMICs) based on single-crystal SiNMs on plastic substrates.

2. Flexible switch fabrication

The fabricated flexible SPST switches are simple examples of flexible circuits, containing a series and a shunt diode, with RF ground-signal-ground (GSG) input and output ports. The fabrication process of the flexible single-crystal SiNM switches on plastic substrates is fully compatible with that used to fabricate active transistors and passive components [12,13], thereby allowing simultaneous IC fabrication.

The process flow is briefly illustrated as shown in Fig. 1. The fabrication process begins with a lightly doped p-type Si (100) SOI substrate with a 200 nm Si top template layer and a 200 nm buried oxide (BOX) layer. The patterned SOI sample is then ion implanted with phosphorus and boron ions. Next, the sample is annealed at 850 °C for 45 min in N_2 [Fig. 1a]. The high energy, heavily dosed ion implantation and high-temperature furnace annealing enable doping concentrations of $\sim 10^{19}$–$10^{20}/\text{cm}^3$ n- and p-type ions and, thus, low parasitic effects (resistance and inductance). These "hot" process steps are critical for fabricating RF/microwave active and passive devices. After ion implantation and annealing, the remaining steps are "cold" steps conducted at temperatures of 120 °C and below.

The 200 nm Si template layer is then patterned and dry etched into strips or membranes with arrays of holes down to the BOX layer [Fig. 1b]. After stripping off the photoresist and wet etching (the sample is put into diluted 49% HF solution at room temperature for ~30 min) from the underlying BOX layer, the top SiNMs are weakly bonded onto the Si handling substrate wafer [Fig. 1c]. The sample is then rinsed thoroughly by DI water and brought into firm contact with a polyethylene terephthalate (PET) substrate of ~175 μm thickness that is spin-coated with an adhesive SU-8 epoxy layer. The SiNM can be lifted off from the handling substrate [Fig. 1d] and flip-transferred onto the PET substrate [Fig. 1e]. A UV exposure step is then used to cure the SU-8. The SiNMs can be transferred onto the plastic substrate with no buckling or deformation, with >90% yield. After this step, a stack layer of 40/500-nm Cr/Au is formed using electron-beam evaporating and lift-off processes for metal contacts, device/circuit interconnects, and RF GSG input/output ports [Fig. 1f].

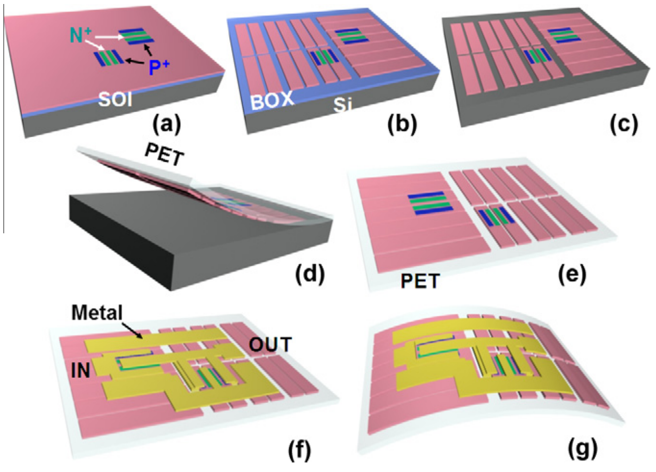

Fig. 1. (Color online) Process schematic of the fabrication process for flexible microwave switches employing single-crystal SiNMs on a plastic substrate (not drawn to scale). (a) SOI sample with heavily doped active regions. (b) A patterned and etched 200 nm template Si layer on a buried oxide (BOX) layer. (c) 200 nm single-crystal Si nano-stripes settled on a substrate wafer by etching away the BOX layer in HF solution. (d) The SiNM detached from the handling substrate and made firm contact with the PET plastic substrate with an adhesive spin-coated SU-8 layer. (e) The SiNMs flip-transferred onto the plastic substrate. (f) Finished flexible microwave single-crystal SiNM switches on a plastic substrate, after the metal interconnection and electrode deposition. (g) Illustration of the flexible switches under bending conditions.

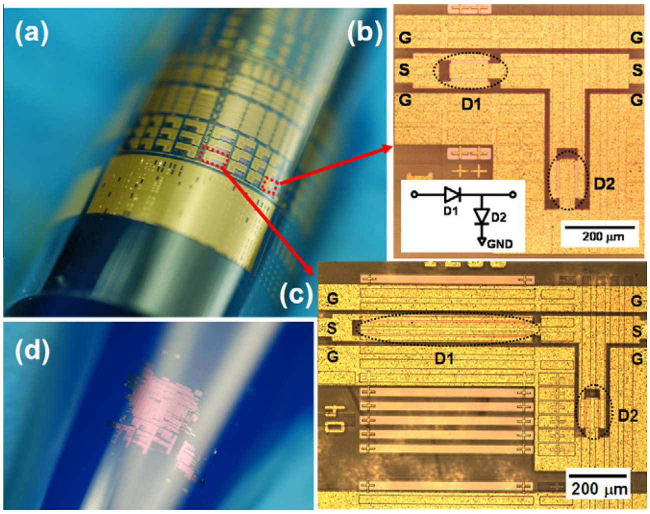

Fig. 2. (a) Optical image of the finished microwave switches on a curved PET substrate. (b) Microscopic image of the flexible microwave switch on a plastic substrate. Switch A: the series diode D1 area is 40 μm², shunt diode D2 area is 40 μm². The inset image shows the switch circuit diagram. (c) Microscopic image of switch B: the series diode D1 area is 240 μm², shunt diode D2 area is 40 μm². (d) Optical image of the single-crystal SiNMs (after dosing and annealing) transferred on plastic substrates.

The series and shunt diodes forming the SPST switches have an intrinsic region width of 2 μm to achieve a high-frequency response while maintaining proper breakdown voltages for power handling. Two types of flexible switches are investigated in this study; the first containing series/shunt diodes (D1/D2) with an area of 40/40 μm² (*switch A*) and the second with an area of 240/40 μm² (*switch B*). Fig. 2a shows an optical image of the flexible switches on a plastic substrate. Fig. 2b and c shows the microscope images of finished microwave switches A and B, respectively. The inset image in Fig. 2b shows the SPST switch circuit diagram containing the series/shunt diodes D1/D2. Fig. 2d shows the optical image of SiNMs transferred onto the plastic substrate [corresponding to Fig. 1e].

3. Experimental results and rf model

The RF characteristics of the SPST switches were measured with an Agilent E8364A performance network analyzer using 150 μm pitch Cascade GSG probes. The probe tip was calibrated with the Short-Open-Load-Thru (SOLT) method with an impedance standard substrate from DC to 20 GHz. Small-signal scattering parameters (S-parameters) were measured for the SiNM SPST switches A (40/40 μm²) and B (240/40 μm²) under both the ON state (series diode is forward biased, forward current $I_f = 10$ mA) and the OFF state (series diode is zero biased). RF signals are transmitted from the IN port to the OUT port [as seen in Fig. 1f]. The power ratio of the signal between the OUT port and the IN port under the ON or OFF state is defined as insertion loss or isolation (S_{21}, in dB), respectively. The power reflection ratio at the IN and OUT ports under the ON or OFF states is defined as the return loss (S_{11} and S_{22}, in dB).

The experimental data for the SiNM SPST switches A and B in the ON and OFF states from DC to 10 GHz are shown in Fig. 3