AIP | Applied Physics Letters

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Citation: Appl. Phys. Lett. **97**, 233110 (2010); doi: 10.1063/1.3521409

View online: http://dx.doi.org/10.1063/1.3521409

View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v97/i23

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Impact of strain on radio frequency characteristics of flexible microwave single-crystalline silicon nanomembrane p-intrinsic-n diodes on plastic substrates

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(Received 12 October 2010; accepted 3 November 2010; published online 9 December 2010)

This letter presents radio frequency (rf) characterization of flexible microwave single-crystalline silicon nanomembrane (SiNM) p-intrinsic-n (PIN) diodes on plastic substrate under various uniaxial mechanical tensile bending strains. The flexible single-crystalline SiNM PIN diode shows significant/negligible performance enhancement on strains under forward/reverse operation modes from dc to 20 GHz. An rf strain equivalent circuit model is developed to analyze the underlying mechanism and reveals unproportional device parameters change with bending strains (~0.4% tensile strain induces ~10% change for diode internal and parasitic inductance/resistance). The study provides guidelines of properly designing and using single-crystalline SiNMs diodes for flexible monolithic microwave integrated circuits. © *2010 American Institute of Physics*. [doi:10.1063/1.3521409]

Increasing interests have been drawn on high performance flexible electronics for the past few years because of their unique advantages such as bendability, light weight, resistance to impact, etc.[1] Amorphous and polycrystalline silicon, organics, and polymers are the most commonly used materials for the low-speed flexible electronics, such as large-area displays, electronic textile/paper, and low-cost integrated circuit.[2–5] Besides these low-speed applications, there is a variety of applications where high-speed and high frequency [e.g., radio frequency (rf) and microwave] operations are highly desired. Examples include RFIDs, personal wireless devices, rollable airborne/space-borne communication systems, surveillance, and remote sensing radars.[1,6] Unfortunately, none of the traditional flexible semiconductor materials can offer the high-speed capability due to their low crystalline quality and low carrier mobilities.[1,4,5] Recently developed transferrable and flexible single-crystalline Si nanomembrane (SiNM) led to a significant step toward fast flexible electronics. With the combined high-temperature and low-temperature process for transferrable SiNMs,[7] we have fabricated a series of flexible microwave active devices (thin-film transistors: TFTs) and passive components (diodes, inductors, and capacitors).[7–10] It unveils the great possibility of flexible monolithic microwave integrated circuits (MMICs) on a plastic substrate.

Since the flexible electronics need to commonly operate under extreme mechanical conditions (e.g., bending), the characterization of the flexible devices under bending strains is essential. Only limited studies show the bending strain's influence on performance of low-speed flexible devices or circuits.[11,12] More importantly, the impact of bending strains on high-speed microwave flexible devices is not yet reported. Considering that the flexible microwave p-intrinsic-n (PIN) diode is one of the most important and basic components in microwave circuits, in this letter, detailed rf/microwave performance for flexible microwave single-crystalline SiNM PIN diodes under bending strains are presented. In addition, to better design the flexible microwave integrated circuits, rf/microwave strain model of the PIN diodes is necessary. In this letter, we develop an rf equivalent circuit model for the microwave PIN diodes using transferable SiNMs on plastic substrate. The model reveals the most influential device factors and underlying mechanism of microwave diode performance change with bending strains.

The process of transferring single-crystalline SiNM and fabricating the microwave PIN diodes is completely compatible with the process used to fabricate microwave TFTs.[7] The detailed fabrication process and scheme can be referred to our previous works.[8,9] Figure 1(a) shows an optical image of the flexible PIN diodes on a polyethylene terephthalate (PET) substrate. Figure 1(b) shows the optical-microscope images of finished lateral SiNM (~200 nm thick) PIN diodes with an area of 240 μm^2, with the corresponding circuit diagram and testing pad configuration.

Rf characteristics of the PIN diode were measured with an Agilent E8364A performance network analyzer using cascade ground-signal-ground (GSG) probes. In order to perform the bending characterizations, the flexible chip was mounted on bending test fixtures with different radii ranging from 77.5 to 21 mm. The flexible microwave PIN diodes were bent along the input-to-output (port) direction, as illustrated in Fig. 2(a). Figure 2(b) shows a picture of the bending test setup with probing on the device.

Small-signal scattering parameters (S-parameters) were measured for the SiNM PIN diodes under both on (diode is forward biased, forward current $I_f=10$ mA) and off (diode is zero biased) conditions with different bending strains. rf signal is transmitted from the input port to the output port.

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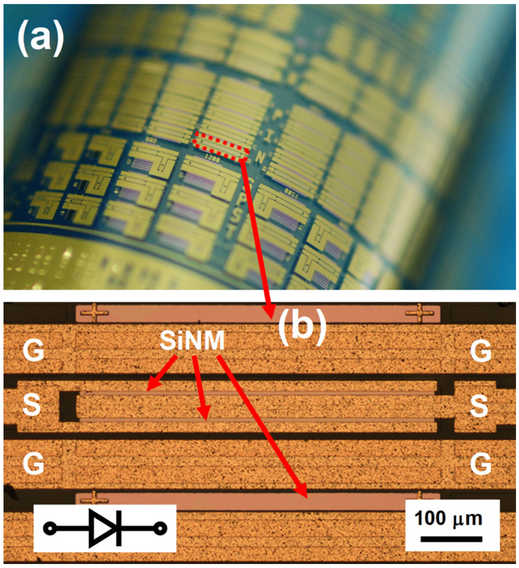

FIG. 1. (Color online) (a) Optical image of finished PIN diodes on a bent PET substrate. (b) Optical-microscope image of a finished PIN diode. The diode area is 240 μm^2. The center metal electrodes (labeled as "S" for "signal") cover two strips of the transferred SiNM and the length of each strip is 600 μm. The metal electrodes labeled as "G" are for grounding.

The experimental data for a 240 μm^2 SiNM PIN diode from dc to 20 GHz are shown in Figs. 2(c) and 2(d) (on state) and Figs. 2(e) and 2(f) (off state). The corresponding uniaxial tensile strains are 0.11%, 0.23%, 0.31%, and 0.42%, respectively. The flexible PIN diode using transferable single-crystalline SiNMs on plastic substrate demonstrates good frequency response at rf and microwave frequency regime. More importantly, with mechanical bending strains, the diode indicates significant rf performance enhancement with up to 0.42% tensile strains under forward mode on state from dc to 20 GHz (over 10% in decibel unit), while no observable change under off state. In order to better understand the underlying mechanism for rf performance change of the flexible diode with bending strains, and moreover to design and use the SiNM PIN diodes in flexible MMICs, an rf strain equivalent circuit model is developed. The model can sufficiently provide an accurate performance at the device/circuit level with fewer model parameters and less computation time, compared with a physical model.[13]

The model topology is chosen based on the flexible single-crystalline SiNM PIN diode structure and layout. The rf/microwave equivalent circuit model for flexible PIN diode on a plastic substrate is shown in Fig. 3(a). Where an intrinsic region resistor R_i and series parasitic resistor R_s are combined as R_{tot} for simplicity. The C_{para} is the parasitic capacitor composed of two parallel plate capacitors between the input and output connection metal [as seen in Fig. 1(b)]. The model is put into Agilent Advanced Design System to calculate the rf/microwave response of the flexible PIN diodes with various bending strains.

Figures 3(b) and 3(c) show the rf performance measurement and calculation consistency for the flexible diode with 0.42% strain under forward mode on states, as an example. Figures 3(d) and 3(e) show the off state case. The discrepancy between experimental data and calculation is mainly because of the fluctuation of the measured data due to worse contact between the GSG probe and thin metal electrode on soft substrate. Comparisons between measurement and calculation results under flat and other strains are not shown here due to the limited paper length. Figures 3(b)–3(e) demonstrate good accuracy of the model. No addition parameters are necessary for the flexible microwave PIN diodes on plastic substrates even presented with mechanical bending conditions. Furthermore, the rf strain model provides us with the most influential device parameters under bending strains.

Forward mode (on state). Figure 3(f) shows the on state parameter value reduction (in percentage) dependence on tensile bending strains for the combined resistance R_{tot} and

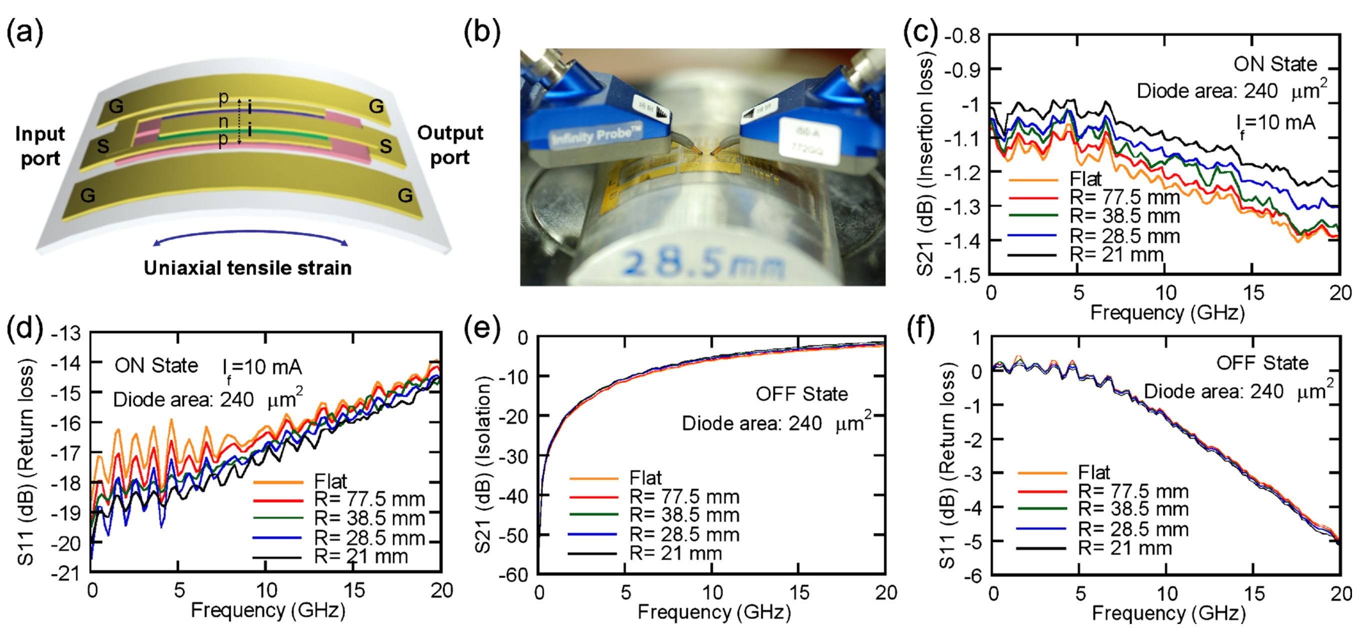

FIG. 2. (Color online) rf characterizations under uniaxial mechanical bending. (a) Illustration of the mechanical bending direction for the PIN diode under bending test. The double arrows show the PIN direction of the diode. (b) Measurement setup for the bending tests of the rf diodes. (c) Measured S21 (insertion loss) and (d) S11 (return loss, S22 is similar to S11, therefore not shown) of PIN diode under on state with bias I_f=10 mA. (e) Measured S21 (isolation) and (f) S11 (return loss) under off state with bias I_f=0 mA. The PIN diode has an area of 240 μm^2. The convex bending radii are 77.5, 38.5, 28.5, and 21, respectively. The corresponding tensile strains are 0.11%, 0.23%, 0.31%, and 0.42%, respectively.

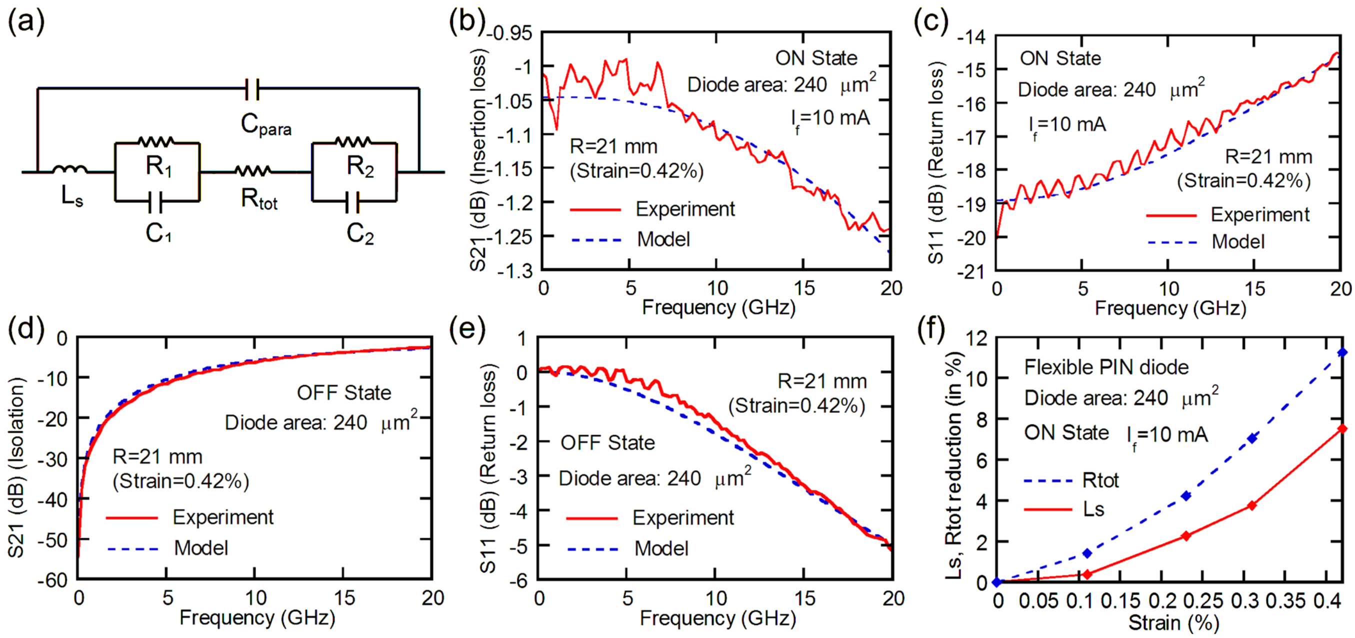

FIG. 3. (Color online) (a) rf strain equivalent circuit model for flexible microwave single-crystalline SiNM PIN diodes on plastic substrate. (b) Measured S21 (insertion loss) and (c) S11 (return loss) of the flexible microwave PIN diode (diode area=240 μm^2) under on state (solid curves) with comparison of the calculated results using developed rf strain model (dashed curves). (d) Measured S21 (isolation) and (e) S11 (return loss) of the flexible microwave PIN diode under off state (solid curves), with comparison of the calculated results using developed rf strain model (dashed curves). The mechanical bending tensile strain is 0.42%, as an example. (f) Forward mode device parameters reduction (in percentage) dependence on tensile bending strains for the combined resistance $R_{tot}(=R_i+R_s)$ and parasitic series inductance L_s, respectively.

parasitic series inductance L_s, respectively. R_{tot} and L_s are significantly and unproportionally decreasing with the larger bending tensile strains, while other model parameters have only a negligible change. There are mainly two reasons. First, the tensile strain is perpendicular to the PIN diode current flow direction [as seen in Fig. 2(a)], therefore the series intrinsic and parasitic resistance/inductance (R_{tot}, L_s) have a larger effective width and smaller effective length as the uniaxial tensile strain increases. Second, as the tensile strain is presented in the PIN diode, the electron mobility of the diode becomes unproportionally larger than the strains. According to the following equation:

$$R_i = \frac{w_i^2}{I_f \tau(\mu_n + \mu_p)},$$

the intrinsic resistance is decreasing significantly larger than the tensile strains.

Reverse mode (off state). When the PIN diode is reversely or zero biased, the junction resistances R_1 and R_2 are open circuit and junction capacitances C_1 and C_2 are very small. Consequently, although R_{tot}, L_s also reduce with tensile strains under off state, they are not the dominant factors. The junction resistances and capacitances have negligible change with tensile bending strains; as a result, the rf performance of the flexible PIN diode has no observable change when the diode is bended.

In summary, we have performed mechanical bending test on rf characteristics of the flexible microwave single-crystalline silicon nanomembrane (SiNM) PIN diodes on plastic substrate. Experimental results indicate significant rf performance enhancement with tensile strains under forward operation mode, while no observable performance change at zero bias condition from dc to 20 GHz. An rf strain equivalent circuit model is developed for flexible single-crystalline SiNM PIN diode to analyze the underlying mechanism and demonstrates that the internal and parasitic inductance/resistance are the most influential factors to rf characteristics with bending strains. The study provides guidelines for properly designing and using single-crystalline SiNMs diodes for flexible monolithic microwave integrated systems.

This work was supported by AFOSR under Grant No. FA9550-06-1-0487. This work was also supported by National Natural Science Foundation of China (NSFC) under Grant No. 61006061 and Ministry of Education of China.

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