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Dark currents

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Semiconductors

Elemental semiconductors

III-V semiconductors

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A flexible silicon barrier diode was fabricated by the transfer printing method. Micro-line patterned p-type single crystalline silicon membranes were created from a silicon on insulator wafer. The dark current of our device was very low, about 1 pA for reverse bias voltages up to 5 V, and showed rectifying behavior with an ideality factor of 1.05. The photo-response and the responsivity was 32 and 0.3 A/W, respectively, for light intensity of 1.2 mW/cm^2. Also, the current of the photodetector changed under compressive stress or tensile stress. Our device is functional as the piezotronic sensor as well as the photodetector. © *2013 American Institute of Physics*.
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Schottky barrier diode (SBD) consisting of a metal semiconductor contact is one of the simplest devices in modern semiconductor technology. SBDs have been attractive in electronics devices such as integrated circuits, photodiodes, and power diodes. Because of its simple device technology, small capacitance, fast response, its demand is increasing in mobile communication and power management.[1,2] III–V semiconductors and SiC SBDs can be alternative candidates to silicon SBDs for higher performance devices; however, the cost of their substrates is much higher than that of silicon substrates. Silicon is a low cost material of high performance, so its application has been studied for silicon photodiodes.[3,4] Especially, Schottky type photodetectors are attractive for their high speed and low noise performance.[5] Schottky type diodes have little minority carrier stored charge and thus can be used for fast switching applications. Since silicon also has piezoresistive characteristics under compressive or tensile stress, it can be used for piezotronic sensors. We fabricated flexible silicon metal-semiconductor-metal (MSM) type SBDs for photodetectors as well as piezosensors by a simple transfer technique. These flexible silicon Schottky devices show diode characteristics because of a distinct difference between the barrier height of silicon/Al and one of silicon/Au. Previous researches, however, have focused on rigid silicon-based devices, so there has been a lack of studies on SBDs based on flexible thin silicon fabricated by the transfer printing technique. Previous transfer printing methods have been used to transfer metal to receiver substrates.[6,7] Our technique is to transfer rigid silicon to receiver substrates such as plastic substrates.

Here, we explain simple transfer printing techniques that are used to fabricate silicon wires (SiWs) SBDs on plastic substrates. We examine both theoretically and experimentally the electrical characteristics of the fabricated flexible SBDs.

Fig. 1(a) schematically illustrates the fabrication process of the SiWs SBDs. The fabrication begins with the formation of micropatterns on the top layer of an SOI wafer (SoitecUnibond^{TM} with a p-type 100 nm top Si layer with doping level of $1.0-4.0 \times 10^{15}$/cm^3) by photolithography (i). After the photolithography process and the reactive ion etching (RIE) steps that defined the 50 μm line patterns, 100 nm-thick silicon was dry etched, and a 200 nm buried oxide layer was undercut with concentrated (49%) hydrofluoric acid for a few hours (ii). By using an elastomeric polydimethylsiloxane (PDMS) stamp, SiWs were picked up (iii) and transferred to the 250 μm-thick polyethylene terephthalate (PET) substrate with the assistance of SU-8 as an adhesive layer (SU-8 2002, Microchem) (iv). After peeling off the PDMS stamp (v), 5 nm/150 nm thick Ti/Al and Ti/Au metals, as cathode and anode, respectively, were evaporated by an e-beam evaporator on top of the transferred SiWs (vi). By this method, a silicon SBD was fabricated on plastic substrates. Fig. 1(b) shows the image of the electrodes of the SBD, which consisted of two different metals, such as Au and Al. The dimension of each metal contact was 1 μm^2 and the distance between contacts was 100 μm. The current-voltage characteristics of SBDs were measured using a semiconductor characterization system (Keithley SCS 4200) in a dark box to avoid any light induced photocurrents. The photosensitivity of the silicon SBDs was characterized with 300 W xenon lamp.

The forward and reverse bias current-voltage characteristics of the SiWs SBDs are given in Fig. 2(a). The resulting SiWs SBDs had breakdown voltages of higher than 10 V and turn-on voltages of around −3 V. The dark current of the diode was about 1 pA for reverse bias voltages up to 5 V. It showed very low dark current due to the high resistivity of the materials and their good rectifying behavior, although its performance was limited by the energy barrier at the metal-semiconductor junction. As seen in the inset of Fig. 2(a), when light was illuminated on the SBD, the current level was about 1 order higher and the turn-on voltage decreased by about 2 V. The current did not saturate when the reverse voltage bias increased.[1,8] The barrier height between a metal and a semiconductor decreases due to image force barrier lowering.[9] This means that the current does not saturate in the reverse bias region. The current-voltage characteristics of a Schottky contact are described by the following equation:[9]

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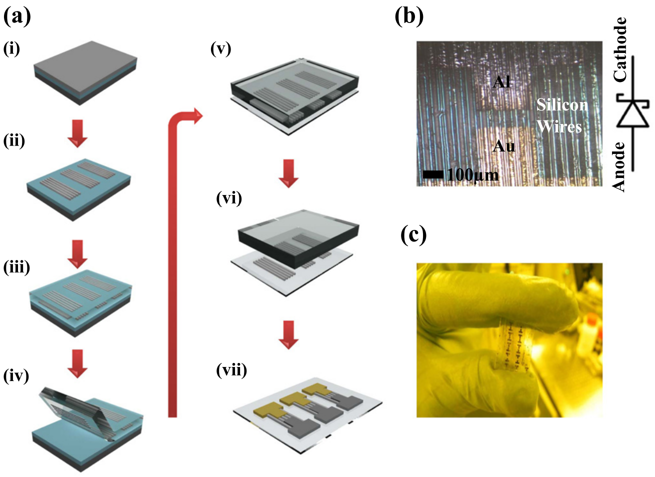

FIG. 1. Fabricating Schottky diodes by using the transfer method. (a) Illustration of the process for the silicon transfer method; (i) beginning with SOI (100 nm p-type top Si and 200 nm buried oxide layer), (ii) patterning of SiWs by RIE, followed by wet etching the buried oxide layer, (iii) attach the PDMS stamp, (iv) peel off the PDMS stamp, (v) transfer the SiWs with PDMS stamp to the adhesive layer coated PET substrate, (vi) peel off the PDMS stamp, (vii) metallization with the e-beam metal evaporation to complete the fabrication. (b) A microscope image of the SBDs on the PET substrate. (c) Photographs of the Schottky diodes on the PET substrate.

$$I = I_0[\exp(qV/nkT) - 1], \tag{1}$$

where $I_0 = A^*AT^2\exp(-q\phi_B/kT)$ is the saturation current, V is the applied voltage, q is the electronic charge, n is the ideality factor, k is the Boltzmann constant, T is the temperature, A is the active device area, A^* is the effective Richardson constant (equal to 30 A/cm^2 K^2 for p-type silicon), and ϕ_B is the barrier height.[10] The ideality factor was extracted from the slope of forward current region and was found to be 1.05. This value is near unity, indicating the high quality of the Schottky diode. The calculated Schottky barrier height (ϕ_B) for the Al and p-type silicon contact is 0.62 eV. The barrier height we calculated agreed with that of the Al/p-type silicon contact.[11] As seen in Fig. 2(b), at the interface between Al and p-type silicon, there was large potential barrier which resulted in a Schottky contact. The as-deposited Ti/Au on the p-type silicon exhibited an imperfect ohmic contact because there was a low barrier height between Au and p-type silicon, which was about 0.2 ~ 0.3 eV.[12] For this reason, our device had a relatively high turn on voltage.

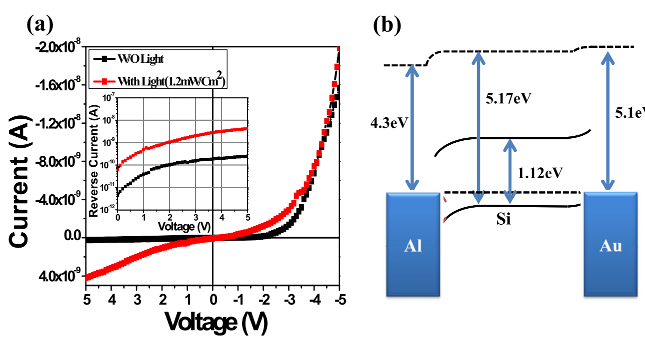

FIG. 2. (a) Current-voltage characteristics of the flexible silicon diode with/without a light illumination. The inset is the log scale of current-voltage characteristics. (b) Band diagram of silicon-metal junction; the barrier height between Al and silicon is 0.62 eV.

However, since the barrier height between Au and p-type silicon was lower than that between Al and p-type silicon, relative ohmic behavior was shown in the p-type silicon with Ti/Au metal. During forward bias operation, if the Al metal is connected to a negative terminal, forward biasing would result as the holes are attracted toward the interface. Then, the depletion region and potential barrier are reduced. Thus, in the forward bias region, there is a large net current. During reverse bias operation, if the Al metal is connected to a positive bias, then reverse biasing would result as the holes are removed from the metal-semiconductor interface. The depletion region and potential barrier are increased. Thus, in the reverse bias region, there is a very low net current.

In Fig. 3(a), we also examined the photo response characteristics of voltage dependent photo-response current versus time as the applied voltage at the cathode increased. The photo-response current at 1.2 mW/cm^2 light intensity increased as the applied voltage at the cathode increased. This occurred because of the large accumulated holes carrier at the silicon layer. Fig. 3(b) shows the photo response characteristics of light dependent photo-response current for the anode-source voltage versus time, while light was illuminated about 10 s for each different light intensity range (0.4 mW/cm^2, 0.6 mW/cm^2, 1.2 mW/cm^2). The photo induced current increased as the light intensity increased. In Fig. 3(b), as the light intensity increases, the photo induced current (= on current) becomes stable in a short time. From these results, we can assume that a multi bit dynamic range is possible under subdivided light intensity and applied voltage because the photo induced current depends on the trend of the light intensity and the applied voltage. From Fig. 3(b), the rise/fall time is also estimated to be about 0.5 s. We think that this large value is due to the high turn-on voltage. Fig. 3(c) shows the variable photo-response according to light intensity. The photo-responses $P = (I_{photo} - I_{dark})/I_{dark}$ of our devices were 12, 16, and 31, respectively. I_{photo} are the on state currents at 0.4 mW/cm^2, 0.6 mW/cm^2, and 1.2 mW/cm^2, respectively, and I_{dark} is the dark current. The calculated responsivity R was 0.3 A/W at 5 V. The external quantum efficiency, $\eta_{EQE} = Rhc/q\lambda$ was measured to be 47% at wavelength of 800 nm, where R is the responsivity, h is Plank's constant, c is the velocity of light in vacuum, q is the electron charge, and λ is the wavelength of light.[13] This efficiency was comparable with those of previous reported photo sensors.[14,15]

Fig. 4 shows that the conductance of the silicon wires increased under compressive stress and decreased under tensile stress. External stress is obtained by[16]

$$\sigma = E_{[110]} \cdot \frac{h}{2R}, \tag{2}$$

where E is Young's modulus, d is the thickness of the silicon, and R is the radius of curvature of the top corner. $E_{[110]}$ was set to 130 GPa, R to 20 mm, and h to 100 nm. By applying 0.3 MPa compressive and tensile stresses to the SBDs, the current at applied voltage of −5 V increased by 150% under the compressive stress and decreased by 86.7% under the tensile stress compared with that of the *in situ* device. This result was consistent with the piezoresistive behavior of a p-type silicon tested by four-point bending

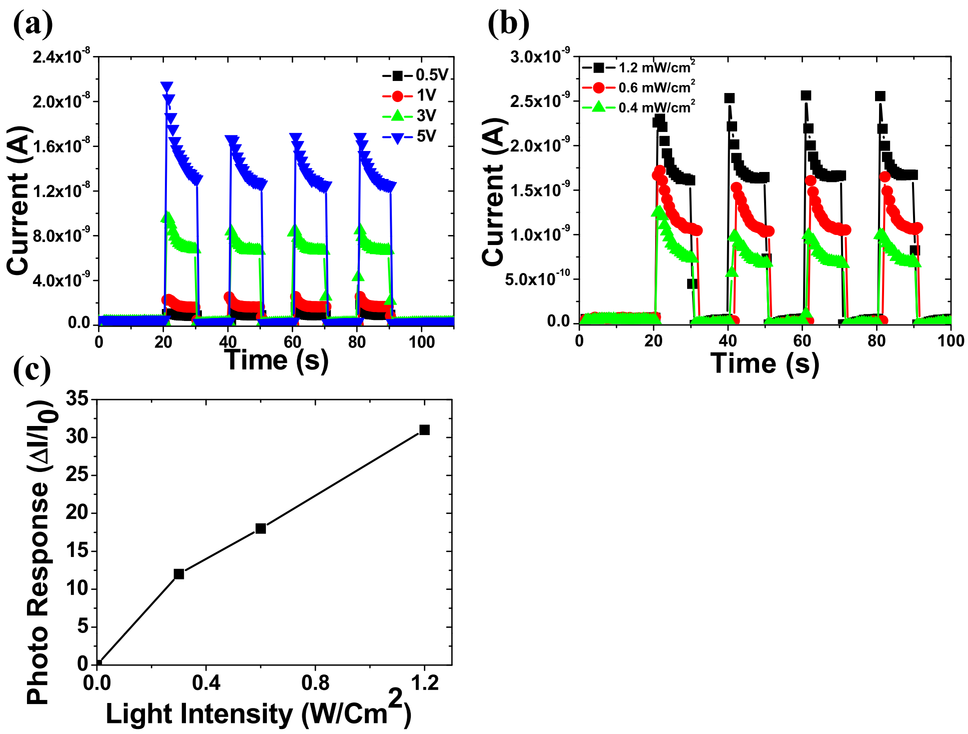

FIG. 3. (a) The current change as a function of time when the diode is exposed to $1.2\,mW/cm^2$ of light intensity and applied voltages ranging from 0.5 to 5 V, (b) the current change as a function of time when the diode is exposed to light intensity is ranged from 0.4 to $1.2\,mW/cm^2$, (c) the variable photo response of the SBD according to light intensity.

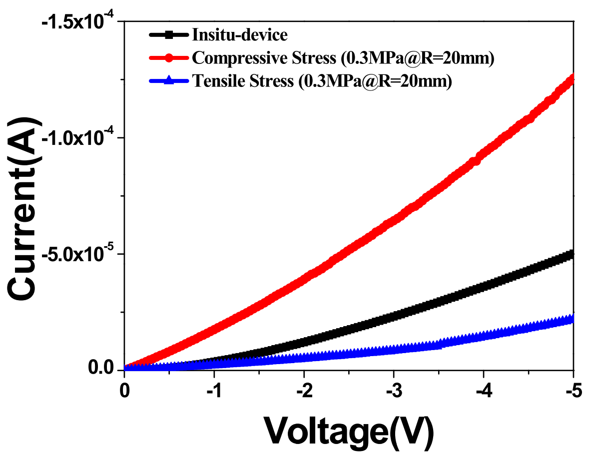

FIG. 4. The current change of the p-type silicon device under tensile or compressive stress.

experiments,[17,18] which are based on the principle that the electrical conductivity of silicon changes when silicon is deformed under applied stresses and that the conductance of the silicon device returns to its original value when the stress is released.[17] Therefore, our SBDs can be used for flexible strain sensors under small stresses.

In summary, we described the fabrication and characterization of SiWs SBDs on plastic substrates. The dark current of our device was very low, about 1 pA, and the measured P was 31 and the R was 0.3 A/W. The current increased by as high as 150% under compressive stress and decreased up to 86.7%. It shows that our flexible SBDs show a big change of conductivity under very small forces (0.3 MPa). Our device is functional devices as the strain sensor as well as the photodetector.

This work was supported by the IT R&D Program (Grant No. 2008-F-024-02, Development of Mobile Flexible (Input/Output Platform) of MKE in Korea, and the Industrial-Educational Cooperation Program between Korea University and Samsung Electronics.

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