Crystalline Silicon Nanomembrane Stacking for Large-Area Flexible Photodetectors

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Abstract

Flexible photodetectors were demonstrated experimentally on large-area crystalline silicon nanomembranes (3 mmx3 mm), based on wet transfer and metal-frame supported transfer processes. Very low dark current (a few nA) and linear photoresponses were demonstrated for both Si MSM and InP PIN photodiodes on flexible PET substrates.

Flexible electronic and photonic structures which can be used to bend, expand and manipulate electronic and photonic devices are of great scientific and engineering importance. Such devices have their applications ranging from flexible imaging/displays, sensors, solar cells and conformal electronic/photonic integrated systems to potential integration into artificial muscles or biological tissues. Most flexible electronics research so far is based on organic, polymer, and/or amorphous semiconductor material systems.

Crystalline semiconductor nanomembranes (NMs), which are transferable, stackable, bondable and manufacturable, offer unprecedented opportunities for unique electronic and photonic devices for vertically stacked high density photonic/electronic integration, high performance flexible electronics, and flexible photonics. High quality single crystalline silicon NMs (SiNM) have been transferred onto various foreign substrates, such as glass, flexible PET (polyethylene terephthalate) plastics, etc., based on low temperature transfer and stacking processes.[1-5] Very high performance electronics based on transferable Si/SiGe NMs were already reported.[1-3] Flexible Ge photodetectors were also reported recently.[6] We have also reported various photonic devices based on Fano resonances on Si, glass and flexible PET substrates.[7-9] In addition to Group IV materials (Si, Ge, etc), nanomembranes based on III-V (GaAs, InP, etc.) and other material systems are also being developed for heterogeneous integration (membrane stacking) on Si and other foreign substrates, with desired electronic and photonic functions.

However, two significant challenges remain in realizing practical large-area photonic devices based on stacked crystalline semiconductor NMs. The first one is the reliable transfer of large-area crystalline semiconductor NMs, especially for the fragile materials systems (e.g. GaAs, InP). The second challenge is the incorporation of metal contacts for the desired electrical properties of photonic devices. Here we report progress made in these two areas by us. In addition to SiNMs, we explored InP NM photodiodes and compared the issues encountered in the two competing NM photodetection technologies. Large-area photodetection was demonstrated for both Si and InP.

Shown in Fig. 1 are the schematics and images of the fabricated two types of large-area photodetectors. The lateral metal-semiconductor-metal (MSM) Si photodetector is shown in Fig. 1(a). The starting material is a SOI wafer with 260 nm thick lightly doped crystalline Si layer on top of 2 μm thick buried oxide (BOX) layer. Release holes were formed first, followed by SiNM layer release process by immersing the SOI wafer into selective wet etchant of BHF solution. Completely released SiNMs were then transferred onto SU-8 coated flexible PET substrate. Finally, Au finger contact was formed on the transferred Si NMs based on metal evaporation and patterned Au wet etching process. Details about the NM transfer process can be found in earlier publications.[1, 9]

Large area InP vertical p-i-n photodiodes were formed with a slightly different process, as shown schematically in Fig. 1(b). The starting material is a p-i-n InP layer (total thickness of 1 μm) grown on top of an InP substrate, with an InGaAs sacrificial layer sandwiched in between. Release holes were formed first on the top InP layer, followed by Au finger contact formation. Due to the weak mechanical properties of InP, it is a significant challenge to transfer larger-area InP NMs without any other supporting structures. The Au finger contact here also offers desired

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mechanical strength for the successful transfer of large area InP NMs. Shown in Fig. 1(c) and 1(d) are pictures and micro-graphs of the fabricated InP photodetector on ITO/PET substrates. Very high quality 3 mmx3 mm InP NM was successfully transferred.

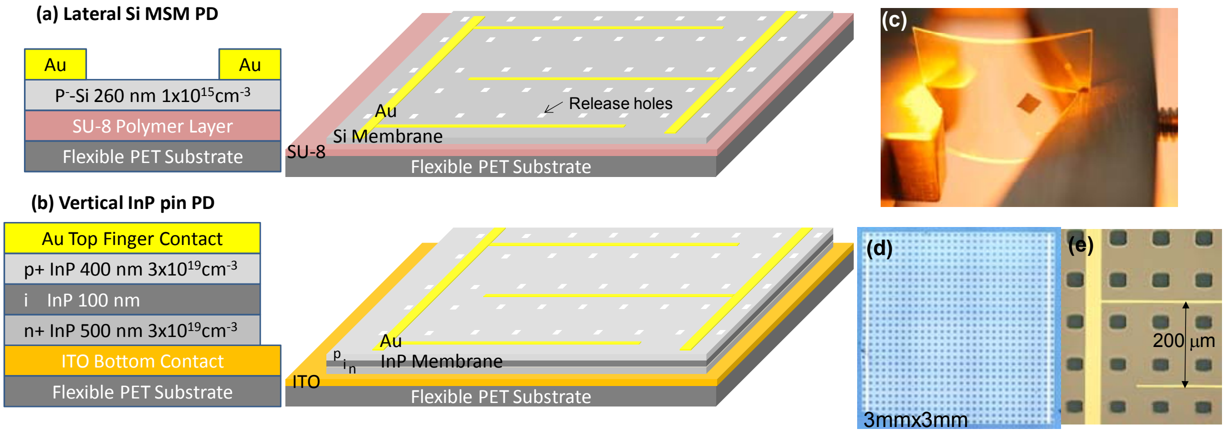
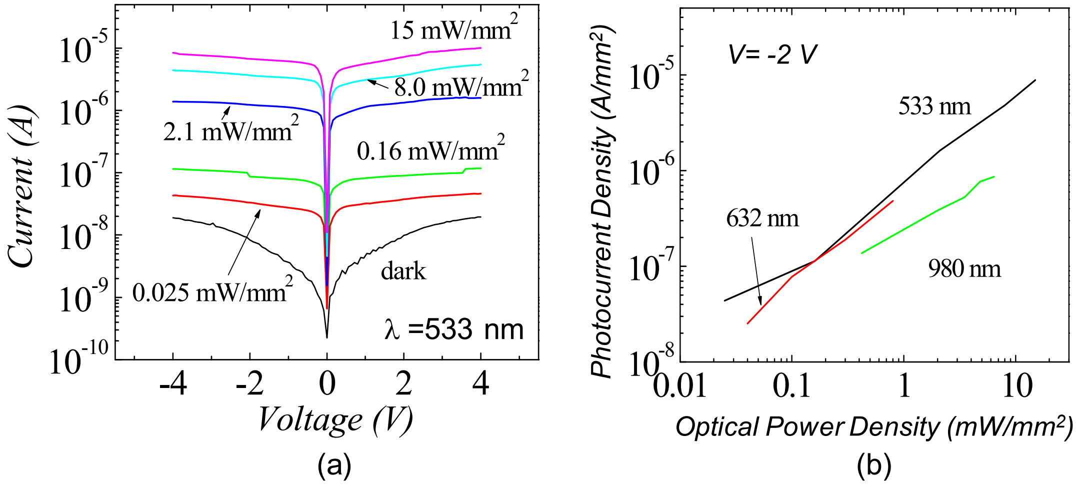


Fig. 1 Schematics of (a) a lateral Si MSM photodetector (PD), and (b) a vertical InP p-i-n photodetector, based on transferred crystalline semiconductor nanomembrane processes; (c) A close-up image, and (d, e) Zoom-in views of a fabricated large area (3x3 mm^2) InP photodetector on flexible PET substrate.

The measured flexible Si MSM photodetector performance characteristics are shown in Fig. 2. Photocurrents were measured with three different laser sources, with wavelengths of 533 nm (a green solid state laser), 632 nm (a red He-Ne laser), and 980 nm (a semiconductor diode laser), respectively. Measured current-voltage characteristics with incident light of 533 nm are shown in Fig. 2(a), along with measured dark current curve. Due to the relatively low doping of the Si layer, very low dark current was obtained with dark current of 8 nA at a bias voltage of +/-2V, for a 3x3 mm^2 device. Very symmetric current-voltage characteristics were obtained for both forward and reverse bias voltages. Considering the effective absorption area with fill factor of 76%, the measured current density was derived and shown in Fig. 2(b) for the three different wavelengths. Very linear photo-response was observed for the power ranges measured. The measured quantum efficiency decreases with the increase of wavelengths, agreeing very well with the absorption characteristics of the crystalline Si.



(a) (b)

Fig. 2 Measured flexible Si MSM photodetector characteristics: (a) Measured dark current and photocurrent with 533 nm light sources at different optical power levels; and (b) Measured photocurrent density at different optical power levels for a bias voltage of -2V, for three different wavelengths (533 nm, 632 nm, and 980 nm).

The measured flexible InP p-i-n photodetector performance characteristics are shown in Fig. 3. The measured current-voltage curve at dark condition is shown in Fig. 3(a). Notice the reverse leakage current starts to increase at

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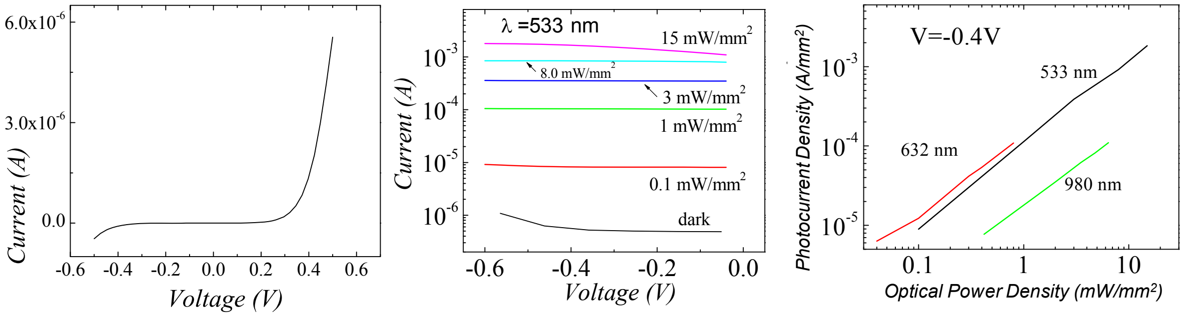
a relatively small reverse bias voltage of -0.6V for this particular device, mostly related to the device fabrication process variations and high doping concentrations. The reverse bias breakdown voltage is greater than -3V for this device and other devices we fabricated. Similar measurements were carried to measure the photocurrents with three different laser sources, with the results shown in Fig. 2(b) and Fig. 2(c). Dark current of 1 μA was obtained for a 3x3 mm^2 device. Very linear photo-responses were observed for the power ranges measured. The best measured quantum efficiencies are similar at the incident wavelengths of 533 nm and 632 nm, with much reduced quantum efficiency at 980nm, close to the absorption edge of InP.



(a) (b) (c)

Fig. 3 Measured flexible InP p-i-n photodetector characteristics: (a) Measured dark current-voltage characteristics; (b) Measured dark current and photocurrent with 533 nm light sources at different optical power levels; and (b) Measured photocurrent density at different optical power levels for a reverse bias of -0.4V, for three different wavelengths (533 nm, 632 nm, and 980 nm).

Further work is being carried out to develop high performance flexible photonic and optoelectronic devices based on stacked crystalline semiconductor nanomembranes, such as multi-color flexible photodetectors, flexible filters, heterogeneous integration of III-V with Si, etc. Advances will be reported in these areas. WY appreciates the help from Dr. Zexuan Qiang and Santhad Chuwongin on detector testing. This work is supported by US AFOSR MURI program under Grant FA9550-08-1-0337. The program manager is Dr. Gernot Pomrenke.

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