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Silicon on Insulator Nanowire Photodiode with Nanoscale Bow-Tie Surface Plasmon Antenna for Light Detection Applications

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Abstract

This work reports the spectroscopic response of fabricated silicon on insulator (SOI) nanowire photodiode with bow-tie surface plasmon antenna for photon detection applications. Surface plasmon antenna is expected to resonantly enhance the electric field near the central gap resulting in increased generation of carriers in the silicon nanowire. Such a photodiode is expected to provide improved quantum efficiency and enlarged light receiving area.

1. Introduction

Silicon on insulator (SOI) [1] nanowire photodiodes (PDs) are expected to realize high speed operation due to the reduced parasitic capacitances, associated with small geometry and lower dielectric constant of the buried oxide below the silicon (Si) layer. However, they suffer from poor sensitivity due to the small Si thickness and the small area for light absorption. By incorporating a surface plasmon (SP) antenna [2], the light absorption efficiency in a small thickness can be enhanced, and the light receiving area can be increased simultaneously.

In this report, a bow-tie SP antenna is incorporated to the Si nanowire PD for the first time, and spectroscopic response for such a PD is investigated.

2. Device Structure

Structure of the SOI PD is shown in Figure 1. It is fabricated on a commercial p-type SOI wafer. The initial impurity (boron) concentration in the SOI and the substrate is 1 x 10^{15} cm^{-3}. Thickness of the top Si layer is 60 nm, which is adjusted by thermal oxidation of the Si and removal of the oxide. The buried oxide thickness is 400 nm. Cathode of the PD is formed by thermal diffusion of phosphorus to achieve concentration >2 x 10^{19} cm^{-3}. Si nanowires of various width (W_{Si}) from 72 to 150 nm have been patterned using electron beam lithography (EBL) and etched using reactive ion etching. Nanowire will act as the photosensitive region of the PD. To enhance the photogeneration of carriers in the nanowire, gold surface plasmon antennas in the shape of a bow tie with designed antenna lengths (L_{ANT}) from 240 to 400 nm have been fabricated. The bow-tie structure is patterned using EBL. After resist exposure and development, 5 nm of titanium and 50 nm of gold are deposited by electron beam evaporation and developed resist is lifted off to fabricate the pattern. The designed channel length (L_C) of the SOI PD is 40 and 72 nm. Bow-tie antenna is a half wavelength surface plasmon antenna, i.e. L_{ANT} is a half of the SP propagation wavelength. When the light enters the antenna, it resonantly excites the SP on the surface of gold. Initially, the bow tie is closed, but a nanogap can be created at the junction by flowing current and inducing electromigration [3]. The excited SP leads to the enhancement of the electric field near the nanogap [4]. Lastly, the optical near field will generate the carriers within the depleted Si nanowire, thereby increasing the cathode current.

3. Experimental method

Figure 2(a) shows the circuit diagram of breaking of bow-tie antenna by controlled passage of current for nanogap formation. The current flowing through the bow-tie antenna is monitored. The resistance at the onset of current flow (before breaking) is calculated to be around 60 GΩ.

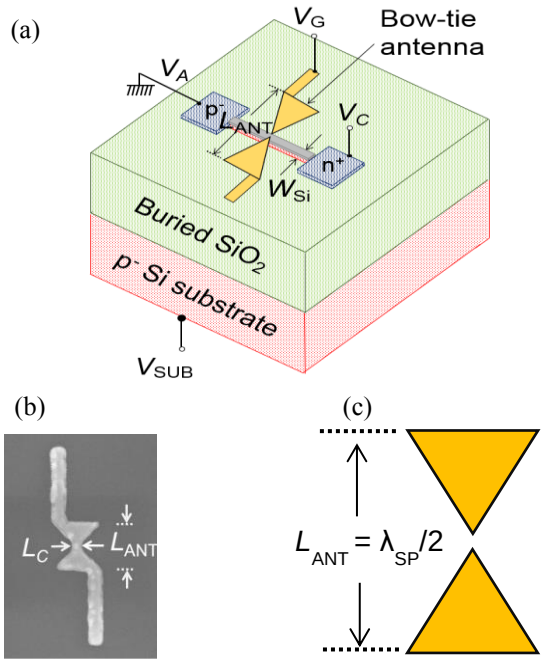

Fig. 1 Device structure of the SOI PD. (a) Schematic diagram, (b) SEM image of gold bow-tie antenna with L_{ANT} and L_C of 240 nm and 40 nm, respectively, (c) Bow-tie antenna design.

As the voltage across the antenna increases, the current also increases. At sufficiently high voltage, the current suddenly drops indicating the breaking of junction by electromigration. The resistance calculated after breaking the bow-tie antenna is more than 2 TΩ.

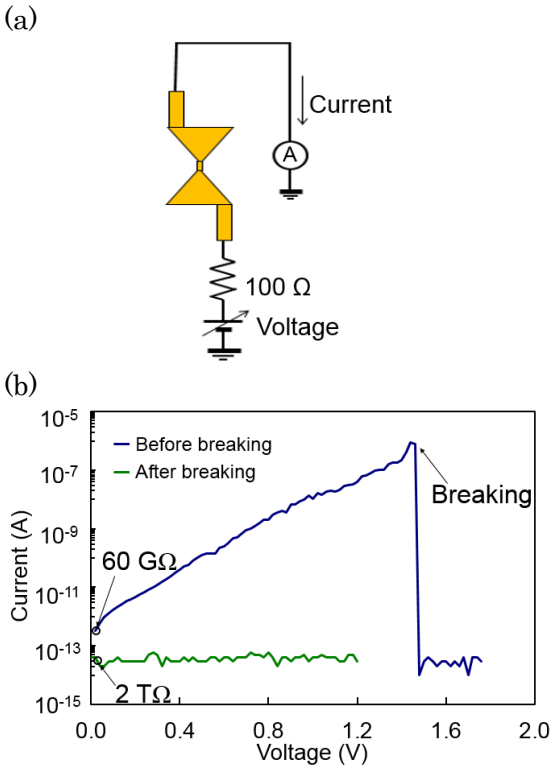

Fig. 2 Break junction for nanogap formation, (a) Circuit diagram of break junction (b) Current vs. voltage curves before and after nanogap formation.

For optical measurements, the device is illuminated by the light through a monochromator with wavelength range of 400 to 700 nm. The spectroscopic response of the SOI PD before and after breaking the bow-tie antenna is measured at $T = 298$ K with biasing of V_C, V_G and V_{SUB} at 1, 0 and -20 V, respectively.

4. Results and Discussion

The resistance before breaking the antenna is around 60 GΩ, which is large. This suggests that the antenna is not properly fabricated. According to our expectations properly fabricated antenna will show a typical resistance value less than 4 kΩ.

Figure 3 shows the effective detector area (A_{Eff}) of the SOI PD with respect to the wavelength, before and after breaking the bow-tie antenna to create nanogap. A_{Eff} is given by equation (1).

$$A_{Eff} = \frac{I_{Ph}}{e} \Big/ \frac{P_{Opt}}{h\nu} \qquad (1)$$

Where, I_{Ph}, P_{Opt}, e, h, and ν are photocurrent, optical power per unit area, electron charge, Plank's constant, and light frequency, respectively.

A_{Eff} shows little change after the junction breaking, probably because the nanogap is not properly formed. Also, the antenna effect is localized, but the effective detector area includes the contribution of the depleted area, which extends all over the device. These may lead to the indistinct antenna effect in the current experiment.

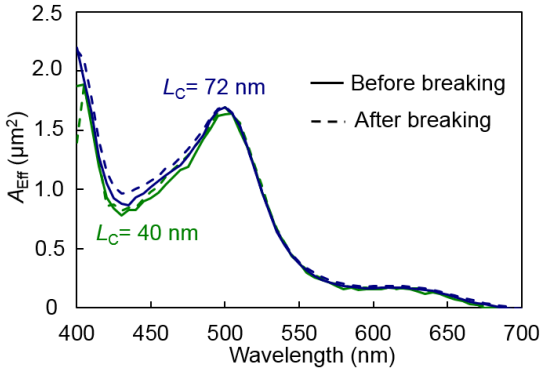

Fig. 3 Effective detector area vs. wavelength. W_{Si}= 150 nm.

5. Conclusions

The process of creation of nanogap in gold bow-tie antenna on SOI nanowire PD, and its effect on the effective detector area of the PD were investigated. Similar characteristics are observed before and after nanogap creation by electromigration, probably because the nanogap is not properly formed and/or the relatively small contribution of the enhanced near field in the overall photocarrier generation.

Acknowledgements

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