The effect of localized surface plasmon on the photocurrent of silicon nanocrystal photodetectors

Sang-Kyun Kim,1 Chang-Hee Cho,1 Baek-Hyun Kim,1 Yong-Seok Choi,1 Seong-Ju Park,1,a) Kimoon Lee,2 and Seongil Im2

1Department of Materials Science and Engineering, Gwangju Institute of Science and Technology, Gwangju 500-712, Republic of Korea
2Institute of Physics and Applied Physics, Yonsei University, Seoul 120-749, Republic of Korea

(Received 30 December 2008; accepted 16 April 2009; published online 6 May 2009)

We report on the photocurrent of silicon nanocrystal (Si NC) photodetectors (PDs) that contain silver (Ag) islands. Here, a larger increase in the photocurrent of Si NC PDs was observed with increasing Ag island size. The maximum increase occurred at the wavelength of the Ag surface plasmon resonance and redshifted as the size of the Ag islands increased. As a result, a 97% increase in photocurrent generation was observed and this was attributed mostly to the coupling of Si NC with the localized surface plasmon of the Ag islands in Si NC PDs. © 2009 American Institute of Physics. [DOI: 10.1063/1.3130744]

Research on silicon nanocrystal (Si NC) photodetectors (PDs) has been actively conducted1–4 because Si NCs have shown intriguing properties such as bandgap control with nanocrystal size,5–7 very fast optical transition,8 and multiple carrier generation.9 Recently, we showed that the photocurrent onset energy of Si NC PD redshifts with increasing Si NC size,10 which opens up the possibility of developing wavelength-sensitive PDs for silicon-based image sensors. However, the absorbance in Si NCs is insufficient to replace current Si wafer-based PDs. Hence, alternative approaches are required in order to increase the absorption in Si NCs.

Metal nanoparticles (NPs) have been known to increase the intensities of electric fields resulting in an increase in light absorption because the optical transition rate is proportional to the square of the electric field amplitude.11 Specifically, the plasmon resonance wavelength of metal NPs can be easily modulated based on their size and shape.12 Also, there have been several reports that show increases in the photocurrent of Si wafer solar cells.13 Si wafer PDs,11,14–16 and organic solar cells17 using metal NPs. In addition, for devices using Si NCs, an increase in the photoluminescence and electroluminescence of Si NC light-emitting diodes using silver NPs has been reported. However, to date, there has been no report that demonstrates an increase in the photocurrent of Si NC PDs or Si NC solar cells using metal NPs. For this reason, this report investigates the effect of silver (Ag) islands on the photocurrent of Si NC PDs. It is found here that the increase in the photocurrent of Si NC PDs could be enlarged by increasing the size of the Ag islands, and this was attributed to the increased absorption of Si NCs by the surface plasmon resonance of Ag islands.

Ag films with thicknesses of 2, 4, 7, and 10 nm were deposited on quartz glass and silicon wafers with a low resistivity of 0.002 Ω cm by e-beam evaporation, followed by a rapid thermal annealing at 600 °C for 1 min in N2 atmosphere. Then, 110 nm thick silicon nitride films, in which Si NCs were spontaneously formed during the film growth, were deposited on the Ag/quartz glass and Ag/silicon wafers by plasma-enhanced chemical vapor deposition using SiH4 and NH3 as the source gases. The average size of the Si NCs was determined to be 3.87 nm from the relationship between the photoluminescence emission energy and the size of Si NCs.19 The surface morphology of the silver and Si NC layers was examined using scanning electron microscopy (SEM) and atomic force microscopy. The transmittance and reflectance of Si NC films with and without Ag were measured using ultraviolet-visible spectroscopy. For current-voltage (I–V) measurements, 300×300 μm2 PDs were defined on the silicon wafers by photolithography. A 200 nm thick In2O3:Sn film (indium tin oxide) as a transparent current spreading layer, and aluminum layers as the front and back metals were deposited by e-beam evaporation. The dark current and the photocurrent were measured using a semiconductor parameter analyzer (HP4145B, Hewlett-Packard) and a light source (Oriel Optical System) that employed a 500 W Hg(Xe)-arc lamp and a monochromator covering a range from 310 to 670 nm.

Figures 1(a)–1(d) show the SEM images of Ag islands on the silicon wafers. The numbers on the left-hand side of the images represent the initial thickness of the Ag film before thermal annealing. After thermal annealing, the continuous Ag films broke into small islands due to differences in the thermal expansion coefficients of Ag and silicon,20 and the figure shows that the surface coverage of the Ag islands is maintained at 20%–25%, irrespective of the Ag film thickness. The Ag islands are almost spherical for the samples with 2 and 4 nm thick Ag films, as shown in Figs. 1(a) and 1(b). In the case of the 7 nm thick Ag film, however, the large Ag islands have an oblate shape; most islands have an oblate shape in the 10 nm thick Ag film samples, as shown in Figs. 1(c) and 1(d). Figure 1(e) illustrates the average lateral size and ratio of lateral size to height of the Ag islands as a function of the initial thickness of the Ag films. The figure shows that the average size of the Ag islands increases and their shape becomes more oblate with increasing thicknesses of Ag films. Finally, Fig. 1(f) presents a schematic diagram of the Si NC PDs used for the I–V measurement. Because the n-type silicon wafer has a very low resistivity of 0.002 Ω cm, the depletion region is negligible in the silicon
wafer, and the very small amount of current from the silicon wafer is expected to contribute to the measured photocurrent.

Figure 2 compares the transmittance spectra of the Si NC films grown on the Ag islands on quartz glass with those of Si NC films. From the figure, the transmittance is seen to decrease with increasing sizes of Ag islands. This phenomenon is attributed to a larger extinction cross section, which increases with increasing the volume of metal islands. The minimum peaks in the transmittance spectra are observed at wavelengths of 462, 487, 503, and 516 nm for Si NC films grown on Ag islands with average sizes of 12, 24, 45, and 90 nm, respectively. This peak shift due to the size of the Ag islands can be partly attributed to the phase retardation of electromagnetic waves when the metal particle size is comparable to the wavelength of the incoming light. The oblate shape of large Ag islands shown in Fig. 1 also causes a peak shift in the transmittance spectra.

Figure 2(b) shows the reflectance spectra of silicon nitride films without Si NC, which were deposited over the Ag islands on Si wafers. The figure shows that the reflectance of Si NC films with Ag does not significantly change in the ultraviolet and infrared regions compared to that of Si NC films without Ag, though the reflectance of Si NC films with Ag increases in most of the visible region. The reflectance peak in the visible region redshifts with increasing sizes of Ag islands and this is quite similar to the redshift in the transmittance peak shown in Fig. 2(a). As such, the results in Figs. 2(a) and 2(b) indicate that the large increase in the reflectance spectra in the visible region in Fig. 2(b) is related to the interaction of light with the surface plasmon of the Ag islands.

Figure 3(a) presents the $I$-$V$ profiles of Si NC PDs with and without Ag islands. Both the dark current and the photocurrent under a 480 nm monochromatic light increase with the size of Ag islands, as shown in Figs. 3(a) and 3(b), respectively. Also, Si NC PDs with Ag islands show a higher dark current under the reverse bias of 10 V than corresponding Si NC PDs without Ag. This result can be attributed to easier carrier injection due to the corrugated interface formed of Si NC films.
by the Ag islands, which induces a higher electric field. To further examine the effects of interface roughness on the photocurrent and the dark current, the normalized photogenerated current of Si NC PDs without Ag is compared to that with Ag islands, respectively. Therefore, the possible increase in the dark current shown in Fig. 4. At a wavelength of 480 nm, the light source wavelength.

**FIG. 4.** (Color online) The normalized photogenerated current of Si NC PDs compared to that of Si NC PDs without Ag vs the size of Ag islands and the light source wavelength.

In summary, we investigated the effect of Ag islands on the photocurrent of Si NC PDs with the Ag islands. Based on this investigation, it was found that the surface plasmon resonance peaks shifted to longer wavelengths as the size of the Ag islands increased. This resulted in a better photodetector performance compared to a photodetector without Ag. However, the transmittance at a wavelength of 480 nm was 54.8%, 18.4%, 11.8%, and 10.5% for Si NC films with these Ag islands, as shown in Fig. 2(a). Thus, the increased photogenerated current with larger Ag islands can be attributed to increased absorption in Si NCs, as determined from the smaller transmittances at larger Ag islands.

This work was supported by the Center for Distributed Sensor Network at GIST, and the Korea Science and Engineering Foundation (KOSEF) NCRC grant funded by the Korea government (MEST) (Grant No. R15-2008-006-02001-0).

13. S. Pillai, K. R. Catchpole, T. Trupke, and M. A. Green, J. Appl. Phys. 101, 093105 (2007).
14. H. R. Staart and D. G. Hall, Appl. Phys. Lett. 73, 3815 (1998).