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Low Dark Current Ge Photodetector with Selectively Grown Si Capping Layer

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Abstract
Selective epitaxial growth of a Si capping layer on Ge is studied to reduce the dark current of photodetectors. Results showed that conformal 16-nm-thick Si capping layers deposited using a dichlorosilane precursor at the relatively low temperature of 670°C suppressed the dark current. Metal-semiconductor-metal photodetectors with the Si capping showed superior dark current characteristics of 1.28 nA/μm^2 and high quantum efficiency for irradiations of 1.31 μm and 1.55 μm.

1. Introduction
Germanium on silicon substrate is currently attracting attention for its expected application to Ge-on-Si photodetectors (PD) [1] in Si-photonics. From the viewpoint of the fabrication process in Ge-PD, Ge in itself is not a chemically stable material because its oxide GeO_x is water soluble. This leads to an increase in surface leakage current due to the formation of localized states on the Ge surface [2]. Moreover, Ge on Si tends to be p-type polarity because any defect in Ge acts as an acceptor [3], and strong Fermi level pinning is formed at the conduction band edge of Ge due to its specific surface state [4]. Because of these two factors, the junction leakage current is considerably large. Applying the passivation/capping layer by SiGe or Si is effective to reduce the above two current components. So far, by optimizing the growth condition, a SiGe capping layer (CL) can reduce the dark current to a low level due to the formation of a Schottky barrier between SiGe and the metal electrode [5]. Although the Schottky barrier height (SBH) for the Si/Ge interface is larger than that for SiGe/Ge, it has been reported that PDs with Si-CL on Ge show a larger dark current [5]. Hence, it would be prudent to carefully investigate the Si-CL growth condition and clarify the current mechanism in PDs with Si-CL in order to further reduce the dark current in Ge PDs.

In this study, we have investigated the effect of Si-CL on selectively grown Ge on the dark current characteristics. Our findings show that the growth temperature of Si-CL remarkably affects the dark current characteristics. A flat Si-CL and a smooth interface can be obtained at relatively low growth temperature, which reduces both surface and junction leakage current.

2. Experiment
Samples were grown by reduced pressure chemical vapor deposition on a 300-mm SiO_2-patterned p-type Si (001) substrate. Germane (GeH_4) and dichlorosilane (DCS, SiH_2Cl_2) were used for the Ge and Si-CL growth, respectively, and H_2 was used for carrier gases. Before the growth, high temperature annealing was performed for native oxide removal. Then, 1-μm-thick Ge was selectively grown followed by Si-CL growth using DCS. In this experiment, we fabricated five samples under different growth conditions. First, the growth temperatures of Si-CLs were set to 670°C, 700°C, and 730°C with the thickness fixed at approximately 16 nm, and second, Si-CL thicknesses were set to approximately 10 nm and 5 nm with the growth temperature fixed at 670°C. To examine the I-V characteristics, the Ge-grown samples were covered by SiO_2 followed by TiN/Al/TiN/Ti contact formation on top of the Si-CL, as shown in Fig. 1. Optical responsivities using a metal-semiconductor-metal (MSM) PD with a ladder type electrode were measured, and transmission electron microscopy (TEM) was used to evaluate the qualities of the Si-CLs.

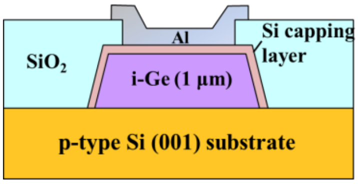

Fig. 1 Cross-sectional drawing of device for I-V measurement.

3. Results and discussion
We measured the I-V characteristics of the single Schottky type devices shown in Fig. 1 by biasing between the top and the backside of the Si substrate. I-V curves and dark current at 5 V are shown in Fig. 2 with changing (a) the growth temperature and (b) the thickness of the Si-CL. On the whole, up to around 3 V, the dark currents were kept at a low level, except for the 5-nm-thick Si-CL grown at 670°C. Above 3 V, differences in the dark current were observed. As the growth temperature increased and the thickness of the Si-CL decreased, the dark current increased. To clarify the components in the dark current, we measured the devices with various peripheral lengths of electrode. Figure 3 shows the dark current as a function of the peripheral length with linear fitting. From the slope and the interception with the vertical axis, we derived the surface (d_s) and junction (d_j) components of the dark current density, as listed in Table 1. Both components increased as the growth temperature increased and the Si-CL thickness decreased.

To clarify the relationship with the band line-up, we derived the SBH between metal and Si-CL from the temperature dependence of the forward bias current [5]. The increase in both d_s and d_j indicates a clear relationship with the reduction of the SBH.

To clarify the behavior of the dark current characteristics, we performed TEM measurements evaluating the crystal quality. Fig. 4 shows TEM images of the Si-CL grown at different temperatures at (a) flat top regions and (b) facet regions of the Ge patterns. With regard to the interface of Si/Ge, the roughness became greater as the Si-CL growth temperature rose at both regions. The roughness became remarkably large at the facet region of the 730°C sample, probably due to the intermixing between Si and Ge during the Si-CL growth. Moreover, the Si-CL became locally thinner at the same region. The above two factors lead to the increase in d_s and d_j due to the formation of localized level acting as a carrier leakage pass together with the reduction of SBH.

Fig. 5 shows the optical responsivity characteristics of the MSM PD with 16-nm-thick Si-CL grown at 670°C irradiated from the top surface. Quantum efficiencies were approximately 33% and 20% for 1.31 μm and 1.55 μm, respectively, with the low dark current density of 1.28 nA/μm^2. These are reasonable considering the Ge thickness of 1 μm and the light shield by the top electrode.

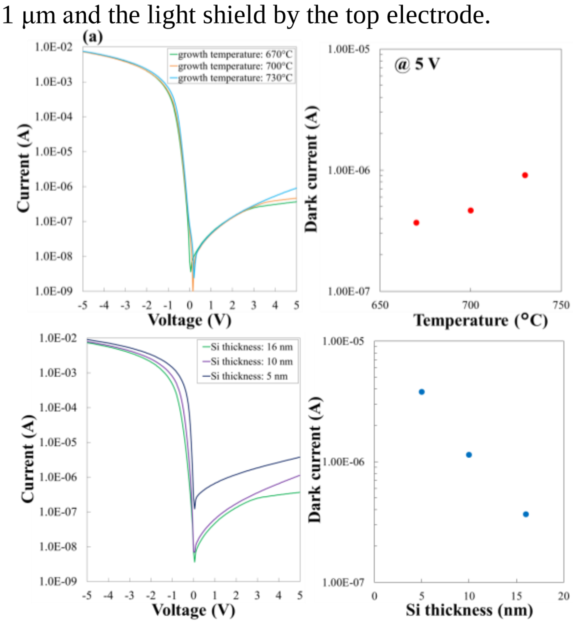

Fig. 2. I-V curves and dark currents at 5 V by changing (a) growth temperature of the Si-CL with 16 nm-thick Si and (b) thickness of the Si-CL grown at 670°C. Size of electrode is 80 μm × 80 μm.

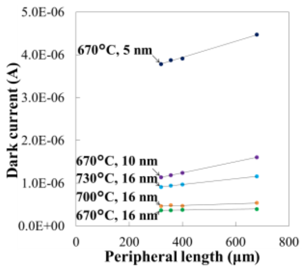

Fig. 3 Dark current at 5 V vs. peripheral length of electrode. Area of electrode is fixed at 6400 μm^2.

Table 1 Surface (d_s) and junction (d_j) components of dark current densities and SBHs between metal and Si derived from temperature dependence results of I-V measurement.

Si-cap condition	670°C 16 nm	700°C 16 nm	730°C 16 nm	670°C 10 nm	670°C 5 nm
d_s(nA/μm)	0.078	0.20	0.68	1.29	1.90
d_j(nA/μm^2)	0.054	0.063	0.11	0.11	0.50
SBH (eV)	0.48	0.48	0.43	0.34	0.25

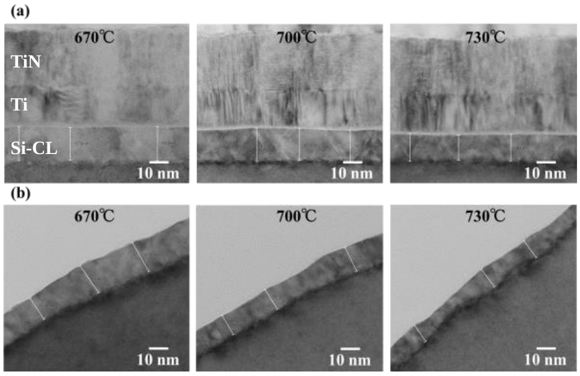

Fig. 4 Cross-sectional TEM images of Si capping layers on Ge at (a) flat top region and (b) facet region grown at 670°C, 700°C, and 730°C.

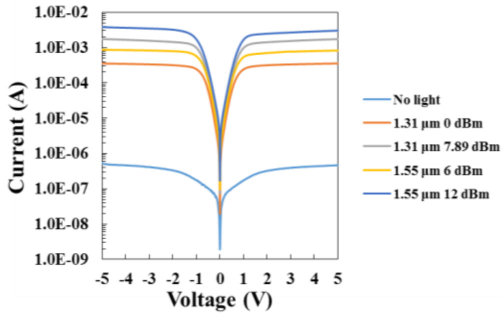

Fig. 5 Optical response measurement of MSM PD to the wavelengths of 1.31 μm and 1.55 μm. Distance of the ladder type electrode is 10 μm and total area of electrode is 360 μm^2.

4. Conclusion

We investigated the effect of a Si capping layer over selective epitaxially grown Ge on the dark current characteristics of Ge-PD and found that conformal 16-nm-thick Si-CL deposited using DCS at the relatively low temperature of 670°C suppressed the dark current. Both surface and junction components of the dark current increased as the growth temperature increased and the Si-CL thickness decreased. As for the performance of MSM PDs, the low dark current of 1.28 nA/μm^2 and high quantum efficiency for irradiations of 1.31 μm and 1.55 μm was demonstrated.

Acknowledgements

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