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Ge/graded-SiGe Multiplication Layers for Low-voltage and Low-noise Ge Avalanche Photodiodes on Si

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Abstract

A new structure of Ge-based avalanche photodiodes on Si is examined, where Ge/graded-SiGe heterostructures are introduced in the multiplication layer. The valence band offset at Ge/SiGe theoretically enhances impact ionizations for holes injected across the interface, being effective for low-voltage and low-noise operations. Epitaxial growth of Ge/SiGe and performances for preliminary devices are also reported.

1. Introduction

Near-infrared pin photodiodes (PDs) of Ge on Si have been widely investigated in Si photonics [1]. Avalanche PDs (APDs) are effective for sensitive photodetections, since photo-generated carriers are multiplied via the impact ionizations under a high electric field. For simple Ge APDs, the multiplication gain is relatively large due to the large ionization coefficients for Ge, while large excess noises are generated, resulting from the ratio of electron and hole ionization coefficients, $k = \beta_h/\alpha_e$, near unity ($k^{-1} \sim 0.7$). Although the so-called dead-space effect in a submicron-thick Ge multiplication layer might reduce the excess noises [2], separate-absorption-and-multiplication APDs have been reported, where Ge and Si were used as the optical-absorption and carrier-multiplication layers, respectively [3]. Si is one of the best materials for the multiplication layer in terms of the low-noise operations, because of the k value far from unity (~0.01). However, the relatively small ionization coefficients lead to high operation voltages (electric field strengths) over ~20 V (~300 kV/cm) [3], which is 2 - 3 times larger than that for Ge APDs.

In this work, a new structure of Ge APDs on Si is proposed, where Ge/graded-SiGe heterostructures are introduced in the multiplication layer for low-voltage and low-noise operations. Epitaxial growth of Ge/SiGe and performances for preliminary devices are also described.

2. Control of impact ionization using Ge/graded-SiGe Heterojunctions

In Ge, the ionization coefficient for holes β_h is slightly larger than that for electrons α_e. Excess noises can be reduced when β_h is preferentially enhanced, corresponding to the k (or k^{-1}) value far from unity. One way for the β_h enhancement is to use heterojunctions in the multiplication layer [4]. Figure 1 schematically shows the band diagram for APDs using an i-Ge/i-SiGe heterojunction in the multiplication layer. The Si composition in i-SiGe is gradually increased from the absorption layer of n-Ge (or nin-Ge), while the Si composition is suddenly dropped at another side of interface to possess a valence band offset ΔE_v. In the n(nin)-Ge absorption layer, electron-hole pairs are generated due to the direct optical absorption, and the generated holes are injected into the i-SiGe layer without any potential barriers due to the graded composition. In the multiplication layer, impact ionizations are enhanced for holes across the abrupt i-SiGe/i-Ge interface, since the kinetic energy for holes is increased by ΔE_v. Assuming that the threshold kinetic energy for impact ionizations (1.0 eV in Ge [5]) is reduced by ΔE_v, β_h was calculated for different ΔE_v as a function of electric field strength F, as in Fig. 2(a). A clear increase of β_h with ΔE_v can be seen even for ΔE_v as small as 0.1 eV, which corresponds to the Si composition of 40% for pseudomorphic (strained) SiGe layers grown on a relaxed Ge layer on Si wafer. Further increase of Si composition is effective to enhance ΔE_v as well as β_h, while the pseudomorphic epitaxy of SiGe on Ge should be an issue in terms of the increase of lattice mismatch.

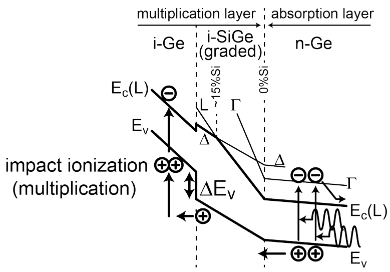

Fig. 1. Schematic band diagram for Ge/graded-SiGe APDs.

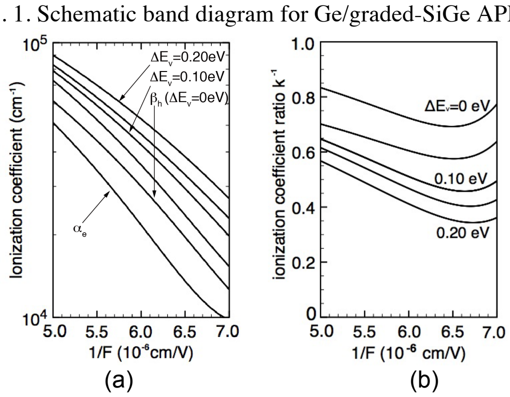

Fig. 2. Calculated (a) β_h and (b) k^{-1} for different ΔE_v.

Such an enhanced β_h should be effective for low-voltage APDs. As for the excess noises, the k^{-1} value was estimated using the results in Fig. 2(a) by simply dividing α_e by β_h. As in Fig. 2(b), the k^{-1} value is less than 0.5 at $F^{-1} \sim 6.5\times10^{-6}$ cm/V (F ~ 150 kV/cm) for $\Delta E_v > 0.1$ eV. Although this value is much larger than that for Si (0.01), the effective k^{-1} value in practical devices can be smaller due to the finite thickness of i-Ge, i.e., the electron ionizations can be suppressed optimizing the thickness of i-Ge while keeping the hole ionizations. Intervalley/alloy scattering in SiGe for electrons, injected from i-Ge, would also suppress the electron ionizations.

3. Fabrication of Ge/graded-SiGe Heterojunctions

Epitaxial Growth of Ge-rich SiGe Layers

Ge-rich SiGe layers are required to realize Ge/graded-SiGe heterojunctions. Si compositions in SiGe were examined for samples grown at 600°C by ultrahigh-vacuum chemical vapor deposition. As the source gases, 9%-GeH_4/Ar and 10%-Si_2H_6/Ar were used. The flow rate of 9%-GeH_4/Ar was fixed to be 140 sccm, while the flow rate of 10%-Si_2H_6/Ar was changed up to 13.2 sccm. The chamber pressure during the growth was ~5 Pa. Figure 3 shows the Si compositions in the SiGe layers determined by x-ray diffraction measurements. The Si composition was found to increase with the 10%-Si_2H_6/Ar flow rate, and the Si compositions up to 47% were obtained.

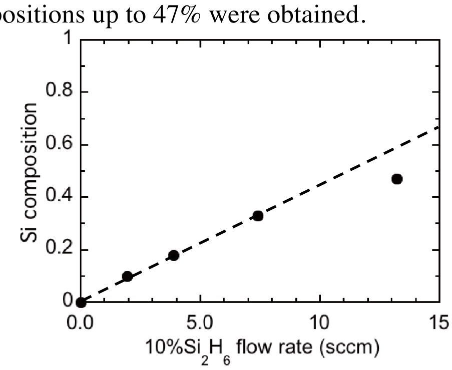

Fig. 3. Si composition in SiGe as a function of flow rate of 10%-Si_2H_6/Ar.

Epitaxial Growth of Ge/graded-SiGe Layers

Using the growth conditions described above, Ge/graded-SiGe layers were grown. Figure 4 shows a typical scanning electron microscope (SEM) image for a fabricated structure. Instead of the continuous change of the Si composition in i-SiGe, three thin (8 nm) layers of SiGe with different Si compositions (30, 20, and 10%) were formed on i-Ge relaxed on p^+-Si (001) substrate, followed by the growth of top Ge layer. The SEM image revealed a successful formation of Ge/SiGe heterostructures.

Performance for Preliminary Devices

After the growth, phosphorous ion implantation was performed to form the top n-Ge absorption layer. Al electrodes were formed for vertical pin diodes. Diodes without SiGe layers were also prepared as a reference. Typical current-voltage (I-V) curves at room temperature under dark are shown in Fig. 5(a). Good rectifying diode properties were obtained. The reverse leakage current of ~100 mA/cm^2 at 1-V reverse bias was obtained independent of the presence/absence of SiGe layers. Figure 5(b) shows typical responsivity spectra at 3-V reverse bias (before avalanche multiplications) under a normal incidence of near-infrared light in the S, C and L bands. The responsivity is comparable between two types of diodes. These results indicate that no severe degradation is caused due to the SiGe layers. As the next step, multiplication gain and excess noises will be measured.

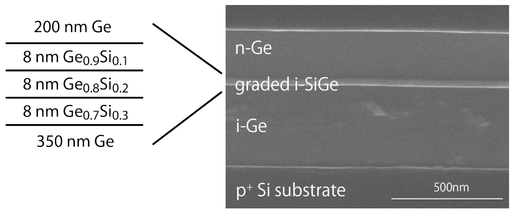

Fig. 4. Schematic cross-section and typical SEM image.

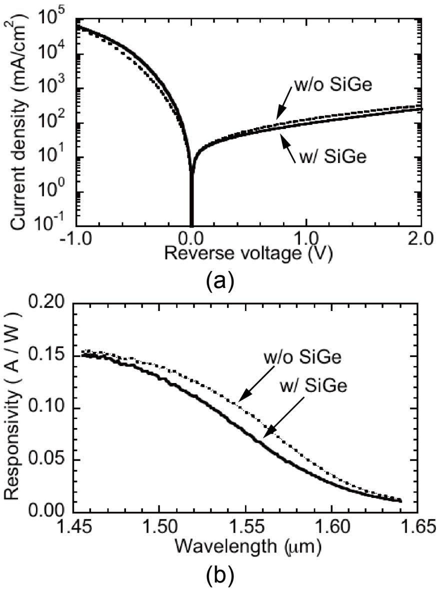

Fig. 5. (a) Typical I-V curves under dark and (b) typical free-space responsivity spectra at a reverse bias of 3 V for fabricated diodes with and without SiGe layer.

4. Summary

A new structure of Ge-based APDs on Si was proposed for low-voltage and low-noise operations, where Ge/graded-SiGe heterostructures are used as the multiplication layer. Epitaxial growth of Ge/SiGe and performances for preliminary devices were also examined, showing promising APD applications.

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