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Staircase band gap $Si_{1-x}Ge_x/Si$ photodetectors

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We fabricated $Si_{1-x}Ge_x/Si$ photodetectors by using a staircase band gap $Si_{1-x}Ge_x/Si$ structure. These devices exhibit a high optical response with a peak responsive wavelength at 0.96 μm and a responsivity of 27.8 A/W at −5 V bias. Excellent electrical characteristics evidenced by good diode rectification are also demonstrated. The dark current density is 0.1 pA/μm^2 at −2 V bias, and the breakdown voltage is −27 V. The high response is explained as the result of a staircase band gap by theoretical analysis. © *2000 American Institute of Physics.* [S0003-6951(00)04528-9]

The band gap of $Si_{1-x}Ge_x$ alloys can be controlled by changing the fraction x and the strain of epilayers. Owing to its full compatibility with silicon technologies, SiGe/Si detectors can be easily integrated. The degree of difficulty and cost of fabrication is much better than that of III–V compound optoelectronic components. For these reasons, in the past decade, many studies of photodetector fabricated on SiGe/Si are noticeable, especially the work on SiGe/Si infrared detectors at wavelengths near 1.3 and 1.55 μm for optical fiber communications.[1–5]

In this work, employing band gap engineering, we describe the staircase band gap SiGe/Si positive-intrinsic-negative (p-i-n) photodiodes working at wavelengths near 1.0 μm. Staircase band gaps encourage impact ionization and may result in multiplication effects.[6] So staircase band gap photodetectors exhibit higher optical response than normal structures. We grew thick $Si_{1-x}Ge_x$ epilayers with graded Ge fractions x on (100)silicon substrates by rapid thermal process/very low pressure-chemical vapor deposition.[7] Ge fractions in $Si_{1-x}Ge_x$ layers vary from $x=0$ to $x=0.35$. According to our previous research,[8] $Si_{1-x}Ge_x$ layers with graded fractions x can decrease the dislocation density of epilayers and improve the quality of crystals. At the same time, the structure of p-i-n junction has a wide depletion layer and will be helpful to collect carriers. The staircase band gap can also enhance the impact ionization of carriers. The discontinuities of the valence band (or the staircase band gap) in the $Si_{1-x}Ge_x$ layer increase the impact ionization, and result in a multiplication effect.

As for the growth condition, SiH_4 and GeH_4 were used as the precursors of Si and Ge. The silicon substrate is n-type (100) with resistivity of 4–7 Ω cm. The growth pressure was about 10^{-3}–10^{-2} Torr and the growth temperature was 600 °C. After growing 200 nm i-Si buffers, we grew ten layers of unintentional doped epitaxial $Si_{1-x}Ge_x$ with graded Ge composition x. The total thickness of the $Si_{1-x}Ge_x$ layers is about 2.1 μm. The Ge fraction x is gradually increased from 0 to 0.35, each layer is about 200 nm thick, and the cap layer is 300 nm (see Fig. 1).

We chose a mesa p-i-n configuration for the detectors (Fig. 1). Mesas were formed by photolithography and plasma ion etching. The light is normal incident and the active areas are 0.09 mm^2. SiO_2 was grown by plasma enhanced chemical vapor deposition at a low temperature (300 °C) and used as the antireflection coating and the passivated film. The contact electrodes were formed by evaporating Al on both sides. On the top, the electrodes were fabricated as rings in order to preserve photosensitive area as much as possible.

The current–voltage characteristics of the $Si_{1-x}Ge_x/Si$ photodetectors were measured. The dark current density is 0.1 pA/μm^2 ($V=-2$ V), which is far smaller than that of Ge, and the breakdown voltage is −27 V. The low dark current and the high breakdown voltage reflect a low defect density of the materials and a high quality of epitaxial crystal. This is due to the thick $Si_{1-x}Ge_x$ graded layers that release strains and decrease the density of threading dislocation.[7]

Figure 2(a) shows the photocurrent density as a function of wavelength. The incident intensity is 0.4 μW. The spectral range we have measured is 0.9–1.2 μm. There are two peaks in the spectral response. One is at 0.96 μm, which corresponds to the photoresponse of Si. The other is at 1.06 μm, corresponding to that of SiGe. Considering the magnitude of the incident light, the photoresponsivity is 27.8 A/W. The photocurrent density as a function of wavelength under

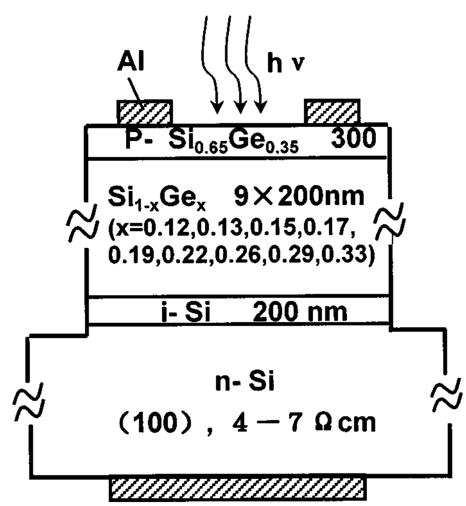

FIG. 1. Schematic of the device. The absorption region consists of ten layers with graded Ge content.

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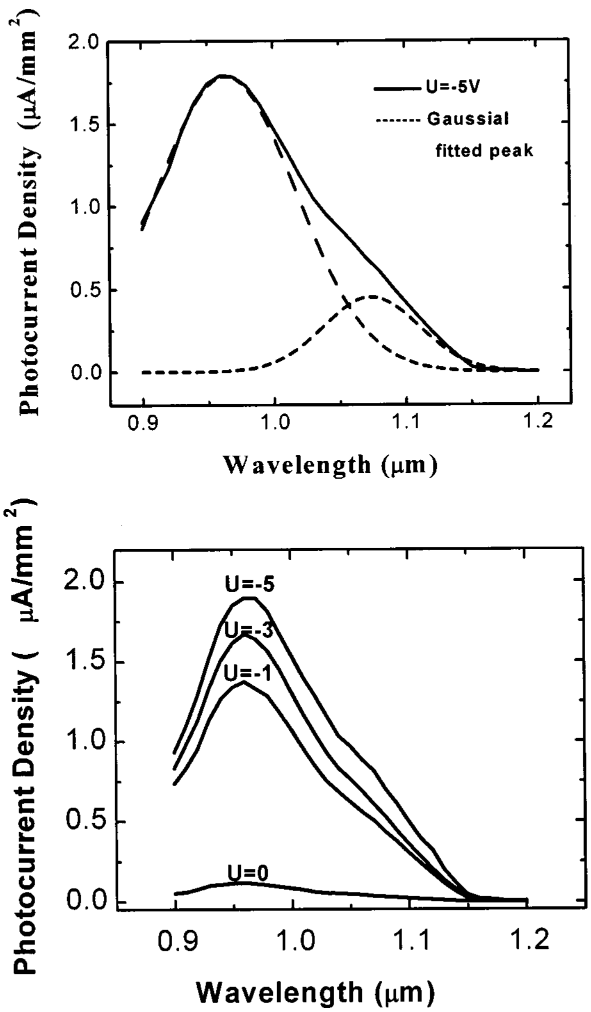

FIG. 2. Measured photocurrent density spectra of the photodetectors. (a) Two peaks can be clearly resolved in the spectra: 0.96 and 1.06 μm. (b) As the applied bias increases, the photoresponse increases sharply.

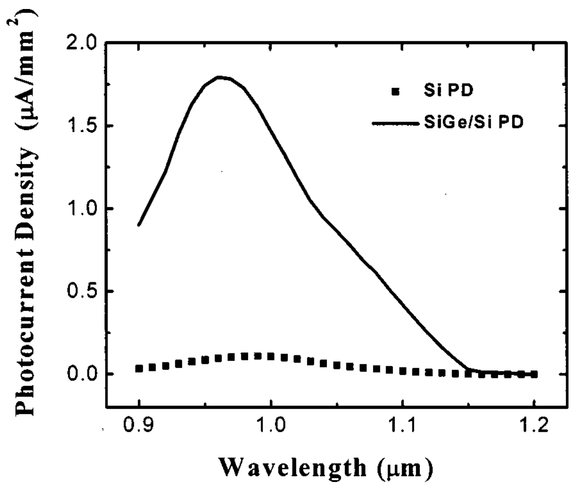

FIG. 3. Photoresponse of the staircase band gap Si_xGe_x/Si photodiode compared with a Si detector at -5 V. The photocurrent density of the $Si_{1-x}Ge_x/Si$ photodiode at 0.94 μm (working wavelength of the commercial detector) is 17 times that of the Si detector.

different bias was also measured and is shown in Fig. 2(b). At zero bias, the photoresponsivity is very low. The photoresponsivity increases fast with an increase of reverse voltage and the photocurrent at -5 V is significantly higher than that at zero bias, indicating bias has a notable effect on photoresponsivity. The increase of photocurrent is mainly due to impact ionization and an increase in the thickness of the depletion layers.

Figure 3 shows the spectral response of the staircase band gap SiGe/Si detectors compared with a commercial Si *p-i-n* detector, which is for remote control. The measurements were made at the prescribed working condition of the Si *p-i-n* detector (at a bias of -5 V and at room temperature) and both active area are 0.09 cm^2. The result is that the photocurrent response of our samples at 0.94 μm (the working wavelength of the commercial detector) is as much as 17 times that of Si detector.

The band structure of a staircase band gap $Si_{1-x}Ge_x/Si$ structure is shown in Fig. 4(a) represents the band structure of the device at equilibrium ($V=0$), and (b) represents that in reverse bias. In reverse bias, the $Si_{1-x}Ge_x$ layer is in a depletion state, and the depletion layer broadens. This broad depletion area provides a wide region where fields collect photoelectrons. Followings the the relation between the band gap and the composition of $Si_{1x}Ge_x$ alloys, $E_g = 1.12-0.74x$, we calculated the band gap of each layer.

From the relation between the fermi level and doping concentration, we also calculated the fermi level. We can conclude from Fig. 4 that there is a large variation in the valence band. The valence band offset ΔE_v is about 0.5 eV from *n*-Si to p-$Si_{0.65}Ge_{0.35}$. In this structure, holes can gain momentum at each concentration step. In addition, they are heated by the electric field. Thus, the impact ionization due to holes is enhanced. Moreover, the band gap of the SiGe alloys are smaller than that of Si, so the ionization rate is larger than that of Si. In the depletion region, holes near *n*-Si layer accelerated as they move towards P region, and the discontinues of valence band enhance this effect. So the impact ionization is enhanced and carriers will be multiplied. But because of the conduction band offsets between Si and Ge, there are small spikes in the conduction band at each concentration step. These spikes tend to impede electron

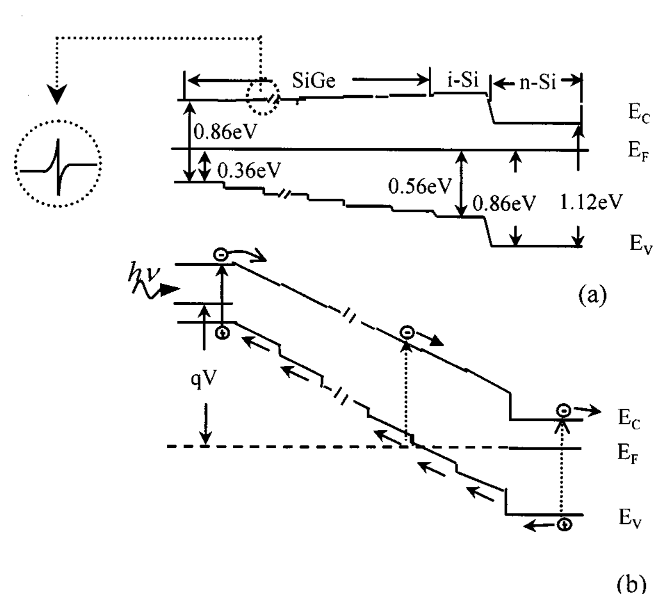

FIG. 4. The band structure of $Si_{1-x}Ge_x/Si$ (a) Under the thermal balance and (b) under the nonthermal balance. The major contribution to carrier collection arises from the valence band discontinue.

conduction. Thus, the holes are likely to be more rapidly accelerated and heated by the external field than the electrons. So the holes may make the most contribution to the high responsivity.

In summary, the staircase band gap $Si_{1-x}Ge_x/Si$ *p-i-n* detectors display good photoresponsive characteristics, and potential for applications. The staircase band gap and the band offset between each sublayer contribute to the improvement of impact ionization for holes and enhancing the multiplication effect on the photocurrent. The graded composition of the SiGe layer also improves the quality of SiGe epilayers.

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