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Intersubband Transition in Si-Based Quantum Wells and Application for Infrared Photodetectors

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Intersubband transitions in quantum wells and superlattices have created a great deal of interest because of their potential applications in infrared detection and imaging. This is particularly important in Si-based heterostructures due to the advantage of monolithic integration with the conventional silicon signal processing electronics. In this paper, experimental observations of intersubband transition in SiGe/Si quantum wells and δ-doped layers in Si will be reviewed. Finally, the progresses in the application of SiGe/Si multiple quantum well structures for the fabrication of infrared detectors will be discussed.

The potential for monolithic integration and the mature processing technology of Si have attracted considerable interest in Si-based optoelectronic devices. Photodetectors operating in the 1.3-1.5 μm range have been fabricated using SiGe/Si multiple quantum wells [1]. The recent development on light emission from porous-Si [2] and SiGe layers have also shed a new light on the optoelectronic application of Si-based structures. In this paper, infrared transitions between subbands of SiGe/Si and δ-doped quantum wells will be reviewed and then the potential application of these transitions in infrared detection will be discussed. Intersubband transition in SiGe/Si system was first observed between heavy hole subbands using p-type multiple quantum wells [3]. Recently, in addition to intersubband transition, transitions between different hole bands (for example, between the light and heavy hole subbsnds) were also observed [4]. The origin of this intervalence band transition can be traced to the coupling of the conduction band with that of the valence band [4]. One of the key advantages of the intervalence band transition is the possibility of normal incidence detection which is forbidden in the case of the intersubband transition [5]. More recently, intersubband transitions in the conduction band have also been observed [6] including normal incidence absorption due to the off-diagonal effective masses for structures grown on specific orientations [7]. In the following, we discuss the experimental results on different subband transitions in the valence band and their application in the infrared photodetectors.

Samples were grown in a molecular beam epitaxy (Si-MBE) system on high resistivity (100 Ω-cm) (100)-Si wafers. For the experiment, four $Si_{1-x}Ge_x$/Si multiple quantum well structures with different Ge compositions, x = 0.15, 0.3, 0.4 and 0.6 and a pure Si δ-doped quantum well structure are used. A period of the SiGe/Si multiple quantum well structure consists of a 40 Å $Si_{1-x}Ge_x$ well and a 300 Å Si barrier. The center 30 Å of the $Si_{1-x}Ge_x$ wells is boron doped to about 5×10^{19} cm^{-3} and the Si barriers are undoped. For the $Si_{0.85}Ge_{0.15}$/Si, $Si_{0.7}Ge_{0.3}$/Si and $Si_{0.6}Ge_{0.4}$/Si samples, 10 periods of multiple quantum wells are grown, while, for $Si_{0.4}Ge_{0.6}$/Si sample, only five periods are grown because of the critical thickness limitation of the SiGe strained layers. The pure δ-doped structure consists of 10 periods of 35Å doped Si layers separated by 300Å undoped Si layers [8]. The absorption spectra of the samples were taken at room temperature using a Fourier transform infrared (FTIR) spectrometer. The nature of the transitions were studied using the polarization dependence of the absorption.

Figure 1 shows the measured absorption spectra of the $Si_{0.4}Ge_{0.6}$/Si quantum well sample at two different polarization angles using a waveguide structure as shown in the inset. At the 0^o polarization angle (electric field having a component in the growth direction as depicted in the inset), an absorption peak occurs at 5.3 μm. At the 90^o angle (beam polarized parallel to the plane), this peak vanishes, but another peak appears at a shorter wavelength, 2.3 μm. The peak at the 0^o polarization is due to intersubband transition between two heavy hole states [9]. This is confirmed by the polarization dependence of the peak [9]. The peak at 2.3 μm shows a

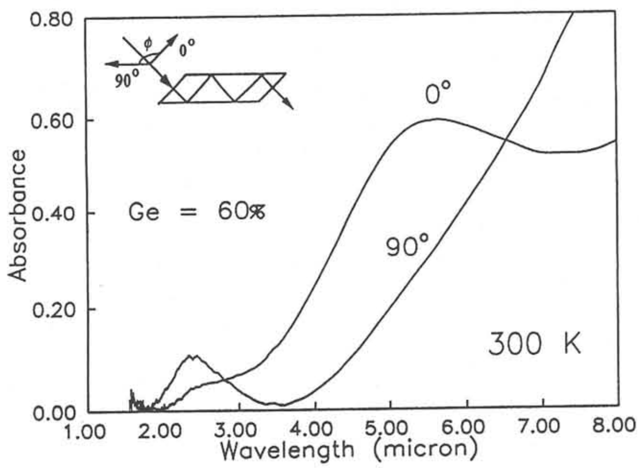

Figure 1: Fig. 1 Measured room temperature absorption spectra of a $Si_{0.6}Ge_{0.4}/Si$ multiple quantum well sample at 0 and 90° polarization angles. The inset shows the waveguide structure used for the measurement.

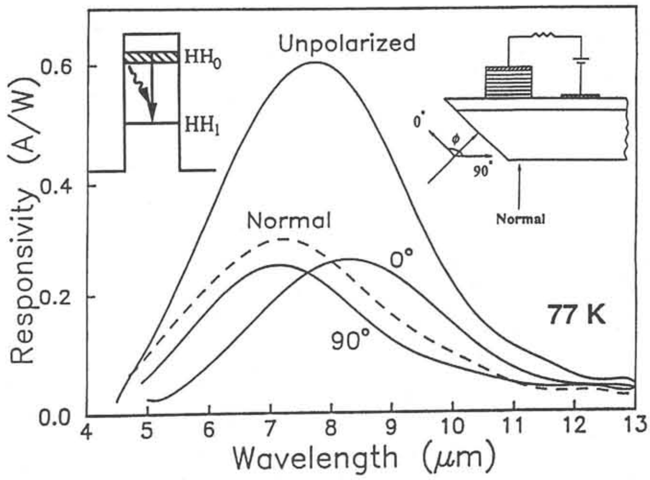

Figure 2: Photoresponse as a function of wavelength for the structure with 15 % Ge composition. Infrared is illuminated on the facet at the normal (see inset) or from the backside of the substrate.

polarization dependence opposite to that of the intersubband transition. At normal incidence (90° polarization), the absorption reaches the maximum and it drops as the angle decreases. Two other samples, $Si_{0.7}Ge_{0.3}/Si$ and $Si_{0.6}Ge_{0.4}/Si$, show similar absorption spectra as the $Si_{0.4}Ge_{0.6}/Si$ sample discussed above [8]. For the sample with a lower Ge concentration (15 %) and the pure δ-doped structure in Si, absorption spectra reveal clear peaks at 0°, due to the heavy hole intersubband transition; however, no obvious peaks are observed at 90°.

The intersubband transitions are found to be between the heavy hole subbands while the intervalence band transitions are between the heavy and split-off hole subbands. The origin of the intervalence band transition is due to the coupling of the conduction band with that of the valence band for high Ge compositions where the Γ band gap is considerably smaller than in Si [4]. Next, we will discuss the application of these transitions for the fabrication of infrared detectors.

For the photoresponse measurement, mesa diodes of 200 μm in diameter were fabricated. The spectral dependence of the photocurrent was measured using a Glowbar source and a grating monochromator with a lock-in detection. Infrared light was illuminated on the mesa at either an angle or from the backside of the wafer depending on the transition process to be probed. Figure 2 shows the responsivity (A/W) as a function of wavelength at 77 K for the structure with 15 % Ge composition in the well for illumination of infrared in different polarizations and directions [10].

It is clear that for the 0° polarization case, the photocurrent is due to intersubband transition between two heavy hole subbands [3] and also partially due to internal photoemission of holes excited via free carrier absorption. For the 90° polarization case, intersubband transition is forbidden but free carrier absorption is stronger than that of the 0° polarization case because entire photon electric field lies in the xy-plane. The photocurrent in this case is believed to be due to internal photoemission of free carriers, since the mixing of the hole bands due to the s-like conduction band or/and nonparabolicity is too small to have significant absorption. The shift of the peak at 90° to a shorter wavelength may be due to the sharing of phonon energy with momentum conserving processes such as phonon or impurity scattering. These provide the normal incidence detection since the free carrier absorption does not dependent on the photon polarization.

The photoresponse of the structures which showed intervalence band transition have been measured using mesa diodes similar to above except that the infrared light is illuminated from the backside of the substrate as schematically shown in the inset of Fig. 3. Responsivity (A/W) spectra as a function of wavelength at 77 K for the samples with 30 % and 60 % Ge compositions are shown in Fig. 3. It can be clearly seen from the measured result that as the Ge composition is increased the peak photoresponse moves towards a shorter wavelength due to the large splitting of the heavy hole and split-off hole bands. In comparison with the absorption data at room temperature, the photoresponse shows several peaks while the absorption spectrum has only one broad peak. The existence of several peaks is due to the transitions to both bound and continuum states which

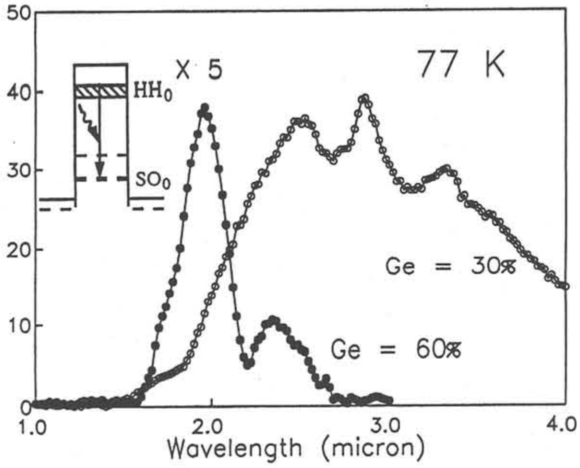

Figure 3: Measured responsivity at 77 K as a function of wavelength for 30 % and 60 % samples. Infrared is incident from the backside of the wafer (normal to the substrate plane) as shown in the inset.

can be discriminated in the photocurrent measurement [11].

The detectivity of the detectors with different Ge compositions was estimated using the measured dark current and the quantum efficiency [12]. For the detector with 15 % Ge, the estimated detectivity at 77 K is about D*(9 μm) = 1×10^9 cm$\sqrt{Hz}$/W while for the one with 60 % Ge is about D*(3 μm) = 4×10^{10} cm$\sqrt{Hz}$/W.

In summary, we have described infrared transitions in Si-based quantum well structures. Both intersubband and intervalence band transitions have been observed using p-type $Si_{1-x}Ge_x$/Si multiple quantum wells. The broad photoresponse covers a large portion of the 3-5 μm and 8-12 μm atmospheric windows. The results demonstrate a new opportunity in the use of the p-type $Si_{1-x}Ge_x$/Si multiple quantum wells for normal incident infrared detection. The demonstration of the normal incident detection shows the potential of using SiGe/Si multiple quantum well IR detectors for future monolithic focal plane array applications.

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