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Local electric field effects in a SiGe quantum well investigated by photoluminescence

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Abstract

We describe photoluminescence and admittance spectroscopy of p-type Si/$Si_{0.75}Ge_{0.25}$/Si quantum-well structures with the SiGe quantum well surrounded by undoped Si spacer layers of various thickness. Holes confined in the SiGe quantum well create a local electric field, which induces potential barriers for holes in the surrounding Si, and a potential well for electrons in the vicinity of the SiGe quantum-well region.

Decreasing the thickness of one of the Si spacers from 30 nm to 5 nm increases the local electric field and shifts the SiGe-related near-band-edge photoluminescence spectrum to higher photon energies. This can be explained by a reduced exciton binding energy due to exciton polarization. The polarization is caused by the increasingly asymmetrical potential well for electrons and holes for the thinner Si spacer layers. In addition, admittance spectroscopy was carried out in order to measure the potential barriers for the confined holes for various thicknesses of the Si spacer layers. For thicker Si spacer layers, the results are in agreement with the photoluminescence data. For thinner Si spacer layers, thermally activated tunnelling of holes via the potential barrier was observed. Our interpretations are supported by theoretical calculations.

Keywords: Field effect; Photoluminescence; Silicon; Germanium; Quantum wells

1. Introduction

Holes confined in a p-type Si/SiGe/Si quantum-well (QW) structure create local electric fields of the order of 10^4 V cm^{-1}. Such electric fields induce potential barriers for holes in the surrounding Si and a potential well for electrons in the vicinity of the SiGe QW region. This may cause confinement of photogenerated electrons. Here we discuss the influence of the local electric field on the band edges. This effect has to be taken into account to obtain accurate energy band-structure parameters for highly doped heterostructures like the SiGe-based modulation-doped field-effect transistor [1]. Photoluminescence (PL) and admittance spectroscopy were performed on p-type Si/SiGe/Si QW structures.

2. Experimental

The p-type Si/$Si_{0.75}Ge_{0.25}$/Si QW structures were grown pseudomorphically on the Si substrates by ultrahigh-vacuum chemical vapour deposition. The Si substrates used for the deposition were (100)-oriented, B-doped with a resistivity of 0.01 Ω cm to 1 Ω cm. The growth temperature was 525 °C, except for the Si buffer layer and Si cap layer which for some samples were grown at 600 °C (Table 1). Details about the epitaxial layer sequence are given in Fig. 1.

The PL measurements were carried out with the samples immersed in liquid helium pumped to about 2 K. An argon ion laser was used as excitation source operating at 514 nm with an excitation density of typically 500 W cm^{-2} focused onto the sample. The spectra were taken with a Fourier transform spectrometer with a liquid-nitrogen cooled Ge photodiode detector. For the admittance spectroscopy, Schottky diodes were prepared by W/Ti deposition and the measurements were performed using a low-frequency impedance analyzer (HP4192A).

3. Results and discussion

Fig. 2 shows low-temperature PL spectra for two samples, which differ only in the thickness of the lower undoped Si spacer layer: 10 nm (upper PL spectrum) and 30 nm (lower PL spectrum), respectively. The near-band-edge PL from the SiGe QW with its well-known spectral components is clearly observed [2]. The peak denoted X^{NP} is the no-phonon peak. The peaks on the low-energy side, X^{TA} and X^{TO} are attributed to phonon-assisted transitions involving transverse acoustic

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Table 1

List of the photon energies for the X^{NP} peak for all investigated samples. The different series of samples correspond to different growth runs. The basic structure is the same for all samples except for the thickness of the lower Si spacer layer. For some samples the Si buffer layer and the Si cap layer were grown at a higher temperature (600 °C) than the rest of the structure (525 °C)

Sample no.	Thickness of the Si spacer (nm)	Photon energy of the X^{NP} peak (eV)	Remarks
Series 1			
C0	10	1.0222	
C1	30	1.0093	
C3	30	1.0103	Si buffer and Si cap grown at 600 °C
Series 2			
C4	30	0.9907	Si cap grown at 600 °C
C5	10	1.0028	Si cap grown at 600 °C
Series 3			
C7	15	1.0410	Si cap grown at 600 °C
C8	5	1.0566	Si cap grown at 600 °C

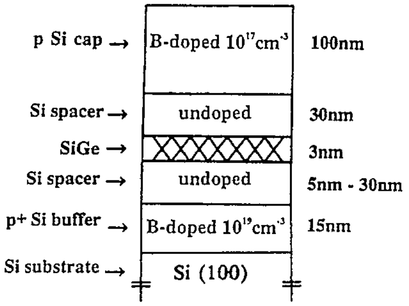

Fig. 1. Schematic diagram of the epitaxial layer sequence of the investigated samples.

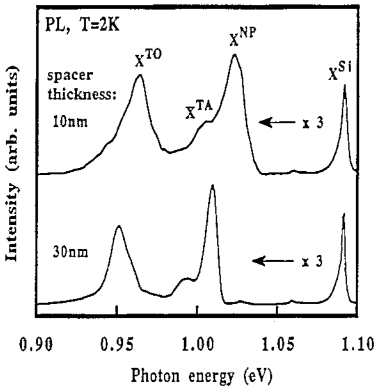

Fig. 2. PL spectra for two SiGe QW structures which differ only in the thickness of the lower undoped Si spacer layer: 10 nm (upper PL spectrum) and 30 nm (lower PL spectrum).

(TA) phonons and transverse optical (TO) phonons, respectively. The peak denoted X^{Si} originates from the Si substrate, and is due to TO phonon-assisted recombination of bound excitons.

The most prominent feature in the PL spectra is that the SiGe-related near-band-edge PL shifts to higher photon energy when the thickness of the Si spacer layer decreases. In the current case the shift is 12.9 meV. This remarkable behaviour was observed for all investigated samples, which involved a number of series of samples with the same basic structure. Hence, a clear trend is present. The results are summarized in Table 1.

As a consequence of the modulation doping (the local electric field), an attractive potential for the electrons in the conduction band in the region near the SiGe QW is present. This potential may cause confinement of the photogenerated electrons and thus, induce a variation in the photon energy. In the following, the shift observed in photon energy for the SiGe-related PL with respect to the Si spacer thickness is compared to theoretical predictions of the confinement energies of electrons and holes, when the Si spacer layer is varied in thickness. The valence-band diagram was calculated by solving the Schrödinger and Poisson equations self-consistently in the Hartree approximation [3]. The valence-band edge was obtained by requiring that the Fermi level remains constant throughout the structure. A valence-band offset, ΔE_v, of 200 meV at the $Si/Si_{0.75}Ge_{0.25}/Si$ heterointerfaces was assumed. The conduction-band was deduced from the Coulomb energy generated by the modulation doping. Fig. 3 shows the calculated band-edges for two structures which differ only in the thickness of the lower Si spacer layer. The confinement energy of the first subband for electrons and heavy holes is also displayed. Decreasing the thickness of the Si spacer layer leads to an upward shift in energy for the electron and the heavy-hole subband. The upward shift in energy is always larger for the heavy hole subband compared to the electron subband, which should result in a reduced energy gap and consequently a reduced photon energy. However, this is in contradiction to the experimental results discussed above.

In our view, the most plausible explanation is that the exciton binding energy has to be considered. A decrease in the thickness of the Si spacer gives rise to a more asymmetric potential well for the electrons and the holes (cf. Fig. 3), resulting in a spatial separation of the charge densities of the electrons and holes, i.e. an exciton polarisation, and thereby a reduced exciton binding energy. The behaviour is illustrated in Fig. 4, which shows the calculated charge densities for the

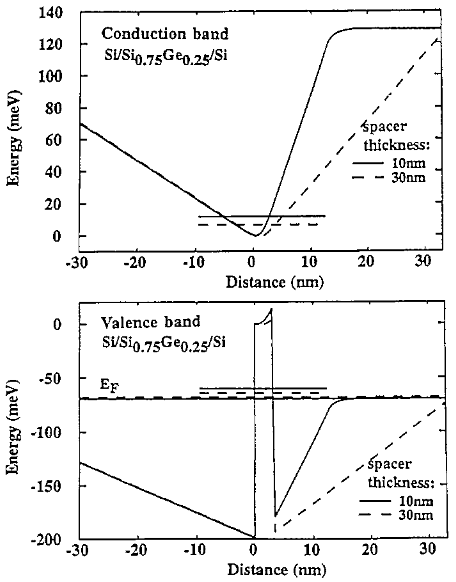

Fig. 3. Calculated band-edges for two QW structures with different thicknesses of the lower Si spacer layer (right side in the figure): 10 nm (———) and 30 nm (- - -). Acceptor concentrations of 2×10^{19} cm^{-3} in the Si buffer layer and 3×10^{17} cm^{-3} in the Si cap layer were assumed.

electrons and holes for two structures with two thicknesses of the Si spacer layer (10 nm and 30 nm).

In a final experiment, admittance spectroscopy (the dependence of the conductance on the measurement frequency [3]) was carried out for structures which again differ only in the thickness of the lower Si spacer layer, from 5 nm up to 30 nm. Schottky diodes were used and the vertical conductance (in the growth direction) was measured as a function of temperature. This in turn gave the activation energy, E_a, for conductance via the potential barriers at the nearby region of the QW. As an example, Fig. 5 shows the results as an Arrhenius plot for two structures, in order to display activated behaviour. $E_a = 21$ meV was determined for the structure with a 20 nm thick Si spacer layer and $E_a = 89$ meV was obtained for the structure with a thicker Si spacer layer of 30 nm. It should be mentioned that for all structures with Si spacer layers of thicknesses ≤ 20 nm, a value of about $E_a \approx 20$ meV was obtained.

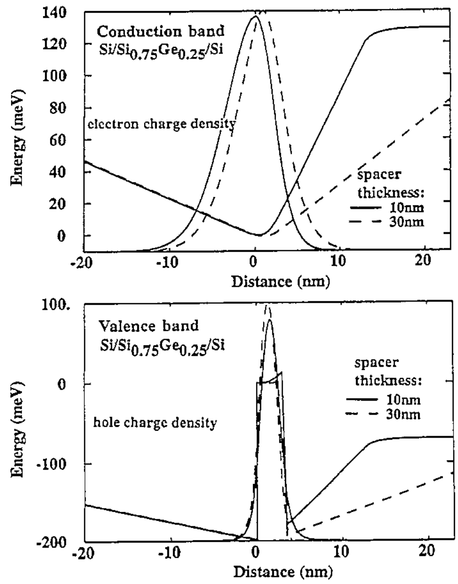

Fig. 4. Charge density profiles for the electrons and the holes for two QW structures with different thicknesses of the lower Si spacer layer: 10 nm (———) and 30 nm (- - -). The band-edges are also displayed. Acceptor concentrations of 2×10^{19} cm^{-3} in the Si buffer layer and 3×10^{17} cm^{-3} in the Si cap layer were assumed.

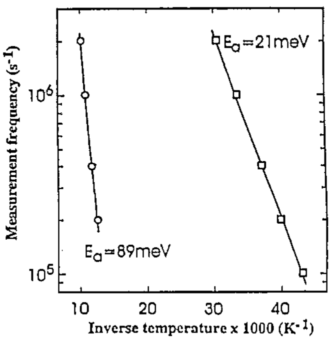

Fig. 5. Arrhenius plot of the measurement frequency of the conductance for two QW structures with different thicknesses of the lower Si spacer layer (20 nm and 30 nm).

In a recently reported admittance investigation on similar samples it was shown that tunnelling through the potential barriers decreases the value of E_a, and that the probability of tunnelling increases for a higher local electric field across the potential barrier [3]. For the presently investigated modulation-doped samples, where one of the undoped Si spacer layers varies in thickness, the concentration of confined holes in the QW (or conversely, the local electric field across the Si spacer layer) is determined by the thickness of the Si spacer layer. Thus, the value of E_a is expected to decrease for structures with thinner Si spacer layers.

The value of $E_a = 89$ meV for the structure with a 30 nm thick Si spacer layer is somewhat lower than the total difference between the SiGe-related X^{NP} photon energy and the Si energy gap. Thermal emission of holes over the Si spacer layer is suggested to be the predominant mechanism. That the value of E_a is smaller than the potential barriers could be explained by a small contribution of tunnelling through the potential barriers, which decreases the value of E_a. On the other hand, for structures with thinner spacer layers, ≤ 20 nm, the value of E_a was found to be independent of the spacer thickness ($E_a \approx 20$ meV). For this mechanism it is suggested that thermally activated processes in the adjacent Si occur, and that the tunnelling effect increases the conductance across the QW so strongly that it is not possible to observe the conductance resonance condition with the admittance set-up used in this experiment (measurement frequencies up to 2 MHz and temperatures down to 30 K).

4. Conclusions

PL and admittance investigations were carried out on p-type Si/Si$_{0.75}$Ge$_{0.25}$/Si QW structures where a SiGe QW is surrounded by undoped Si spacer layers of various thicknesses. Decreasing the thickness of one of the Si spacers increases the local electric field. The SiGe-related near-band-edge PL spectrum shifts to higher photon energy. This observation can be explained by a reduced exciton binding energy due to exciton polarization. For structures with thick Si spacer layers, the results of the admittance spectroscopy are in agreement with the PL data. For structures with thin Si spacer layers, thermally activated tunnelling of holes via the potential barrier occurs.

This study shows that PL spectroscopy is a very sensitive method to investigate local electric field effects in modulation-doped heterostructures. The information gained can be used to obtain accurate energy band-structure parameters of highly doped heterostructures.

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