Intersubband absorption in p-Ge/SiGe quantum wells grown on Si

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***Abstract*—Intersubband absorption from p-Ge quantum wells grown on Si is demonstrated. The absorption can be tuned by adjusting the quantum well thickness. FTIR transmission measurements on as-grown wafers show broad absorption corresponding to intersubband transitions.**

I. Introduction

There is an increased interest to develop Si based detectors that cover the important transmission windows within the mid-infrared (3-5 and 8-12 μm wavelength) to enable on-chip biological and gas sensing spectroscopy. Currently the gold standard for detection at these wavelengths is HgCdTe due to its inherently large detectivities from interband absorption [1]. Disadvantages with HgCdTe is that it is fragile, has low process uniformity, and is not easily integrated with Si. Therefore, to realise on-chip sensors an alternative is required. A good candidate is quantum well (QW) infrared photodetectors. Since absorption can occur from intersubband transitions within the QW, the absorption can be tuned by adjusting the well width, thereby changing the energy of the confined subband states. This has been previously demonstrated with SiGe [2, 3]. Due to the advent of new growth technologies such as low energy plasma enhanced chemical vapour deposition (LEPECVD), it is now possible to grow high quality Ge QWs on a SiGe strain relaxed virtual substrate [4]. This paper demonstrates, to-date, the first experimentally observed intersubband absorption for p-Ge QWs grown on Si.

II. Design and Modelling

The design consists of p-type compressively strained Ge QWs of either 4, 5, or 6 nm thickness, strain symmetrised with $Si_{0.5}Ge_{0.5}$ barriers. This allows the growth of a potentially unlimited number of periods without ever exceeding critical thickness limitations, thereby increasing overall absorption. Another benefit of p-Ge QWs is that it should provide larger absorption coefficients compared to p-SiGe designs, due to the smaller effective masses of the holes. In addition, by using the more complex non-parabolicty and strong coupling of the valence bands, this relaxes selection rules and allows both TE (x-y) and TM (z) polarization. Hence, both surface normal and waveguide geometry devices can be realised. The band energies and confined wavefunctions were calculated using a self-consistent 6-band **k.p** Poisson-Schrodinger solver with the deformation potentials from reference [5]. Figure 1 shows the calculated band structure for a 5 nm Ge QW and 3.1 nm $Si_{0.5}Ge_{0.5}$ barriers. It is clear that the ground state in the QW is HH1 due to strain splitting of the HH and LH bands. The HH2, LH1, and HH3, LH2 are at roughly the same energies within the QW.

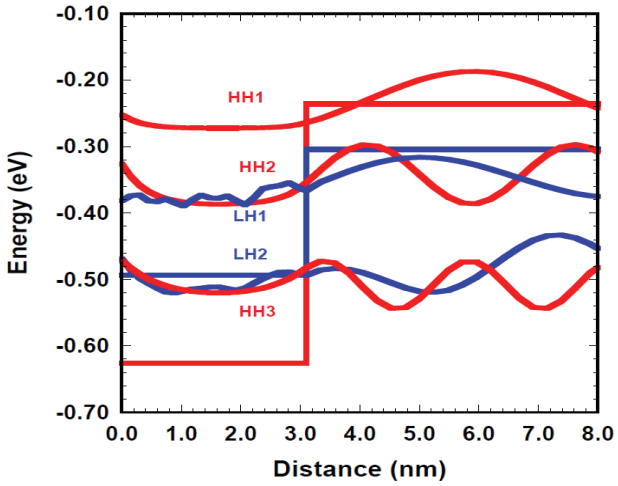

Figure 1. The calculated band structure for a 5 nm wide Ge quantum well, showing the squared wave functions for the lowest energy subband states for the heavy hole (HH) and light hole (LH) bands.

III. Growth

The designed Ge QW structures were grown on a Si substrate by LEPECVD. As previously stated, this growth technique allows the realisation of Ge rich superlattice structures. A 600 nm linearly graded buffer from Si to $Si_{0.2}Ge_{0.8}$ was first grown, followed by a 400 nm p-$Si_{0.2}Ge_{0.8}$ bottom contact region ($N_A = 5\times10^{18}$ cm^{-3}). Then an undoped 10 nm $Si_{0.2}Ge_{0.8}$ spacer region was grown followed by the active region consisting of over 400 periods of either 4. 5, or 6 nm doped QWs (N_A =

5×10^{18} cm^{-3}) sandwiched between 3.1 nm $Si_{0.5}Ge_{0.5}$ barriers. Lastly, another undoped 10 nm $Si_{0.2}Ge_{0.8}$ spacer layer was grown, followed by a 20 nm p-$Si_{0.2}Ge_{0.8}$ top contact region. Graded buffer layers and the fully strained state of the superlattice were observed by x-ray diffraction (XRD). Figure 2 shows the XRD spectra for the 6 nm QW structure. The Si(004) peak of the substrate is visible at q = 7.365 nm^{-1} and is used as a reference. Superlattice fringes are visible with a spacing that indicates a period of ~10 nm. The zeroth-order fringe at 7.051 nm^{-1} is matched to the virtual substrate and indicates an average Ge content of 80% in the active layer stack.

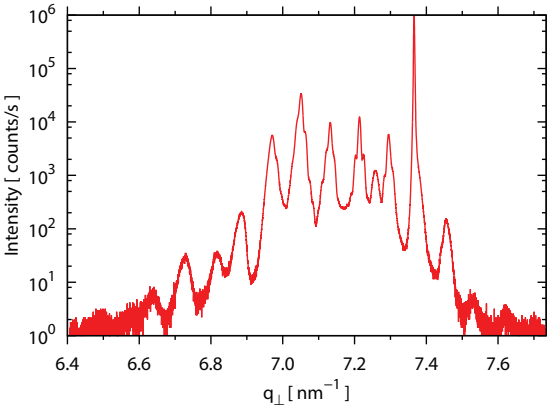

Figure 2. X-ray diffraction curves for the 6 nm wide Ge quantum well structure with 3.1 nm SiGe barriers grown on a Si substrate.

IV. CHARACTERISATION

Fourier transform infrared (FTIR) transmission measurements were performed on the as-grown wafers in vacuum at temperatures down to 6 K. The setup consisted of a Bruker IFS 66 v/s spectrometer with a SiC glow bar as the MIR source and a LN_2 cooled HgCdTe detector. Blank chips of the grown wafers were diced and then bonded onto a cold finger of an Oxford Instruments closed cycle optical cryostat for surface normal transmission. Figure 3 (a) shows the transmission spectra at 300 K for the as-grown structures with QW widths of 4, 5, and 6 nm. The overall low transmission of each spectra is due to the strong free carrier absorption from the heavily doped structures. The absorption peak at ~ 9 μm wavelength, which is visible in all the spectra, corresponds to oxygen impurities within the Si substrate. Each QW structure exhibits broad absorption. There is a clear absorption shift to lower wavelengths for thinner QWs, which is expected, due to the higher energy transitions between confined subband states. From the modelling, this corresponds to transitions between HH2-HH3, HH2-LH2, and LH1-LH2. This illustrates how the absorption can be tuned by changing the QW widths. Figure 3 (b) shows the low temperature transmission spectra of the 6 nm QW structure. It is clear that as the temperature decreases the absorption is increasing. There is negligible blue shift observed, due to the small temperature dependence on intersubband transitions compared to interband.

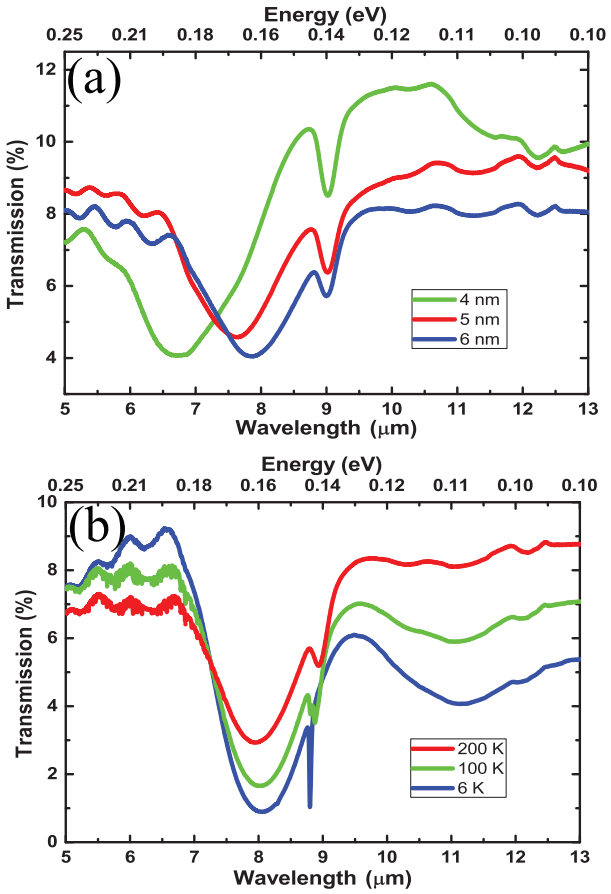

Figure 3. (a) FTIR transmission spectra at 300 K under vacuum for the as-grown 4, 5, and 6 nm wide Ge QW structures. (b) Low temperature FTIR transmission spectra of the 6 nm QW structure.

V. CONCLUSION

Intersubband absorption of p-Ge/SiGe QWs with different widths has been demonstrated. Band structure modelling has been undertaken and designs have been grown. High quality growth of the Ge QWs has been confirmed through XRD analysis. FTIR transmission measurements in TE (surface normal) polarization show broad absorption that shifts to lower wavelengths for thinner QWs. It is envisaged that such designs could produce waveguide coupled photodetectors for on-chip spectroscopic sensing in the MIR.

VI. REFERENCES

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