Picosecond intersubband dynamics in p-Si/SiGe quantum-well emitter structures

P. Murzyn, C. R. Pidgeon, J.-P. R. Wells, and I. V. Bradley
Department of Physics, Heriot-Watt University, Edinburgh, EH14 4AS United Kingdom

Z. Ikonich, R. W. Kelsall, and P. Harrison
School of Electronic and Electrical Engineering, University of Leeds, Leeds, LS2 9JT United Kingdom

S. A. Lynch and D. J. Paul
University of Cambridge, Cavendish Laboratory, Madingly Road, Cambridge, CB3 0HE United Kingdom

D. D. Arnone
Toshiba Research Europe Ltd., 260 Science Park, Cambridge, CB3 0HE United Kingdom

D. Norris and A. G. Cullis
Department of Electronic Engineering, University of Sheffield, Sheffield, S1 3JD United Kingdom

(Received 18 October 2001; accepted for publication 16 December 2001)

We report time-resolved (ps) studies of the dynamics of intersubband transitions in p-Si/SiGe multiquantum-well structures in the far-infrared (FIR) regime, \( \hbar \omega < \hbar \omega_{LO} \), utilizing the Dutch free electron laser, entitled FELIX—free electron laser for infrared radiation. The calculated scattering rates for optic and acoustic phonon, and alloy scattering have been included in a rate equation model of the transient FIR intersubband absorption, and show excellent agreement with our degenerate pump-probe spectroscopy measurements where, after an initial rise time determined by the resolution of our measurement, we determine a decay time of \( \sim 10 \) ps. This is found to be approximately constant in the temperature range from 4 to 100 K, in good agreement with the predictions of alloy scattering in the Si\(_{0.78}\)Ge\(_{0.22}\) wells.

\[ \text{ DOI: 10.1063/1.1452794 } \]

\( p \)-type Si/SiGe quantum wells (QWs) are prospective candidates for intersubband (quantum cascade) lasers operating at mid- or far-infrared [(MIR) or (FIR)] wavelengths.\(^1\) Possible advantages over other systems include the absence of polar optical phonons, the increased phonon energy in Si relative to most III–V materials, the existence of both the in-plane and \( z \)-polarized optical intersubband transitions [enabling vertical-cavity surface emission lasers (VCSELs)], and the low cost of material processing with the potential for on-chip integration. MIR emission,\(^2\) and ultrafast time-resolved studies of the intersubband transitions,\(^3\) have been reported from this system, at photon energies greater than the optical phonon energy (\( \hbar \omega > \hbar \omega_{LO} \)). In the present work we report time-resolved studies of the dynamics of intersubband transitions in \( p \)-Si/SiGe multiquantum-well structures in the FIR regime, \( \hbar \omega < \hbar \omega_{LO} \), utilizing the Dutch free electron laser [Free Electron Laser for Infrared Radiation (FELIX)]. Although the ultimate aim of our program is to produce terahertz (THz) emitters in the VCSEL configuration, special transmitting prototype structures were designed and grown for the FELIX measurement of intersubband dynamics.

Our structures comprise ten modulation doped Si\(_{0.78}\)Ge\(_{0.22}\) QWs with Si barriers, and Si\(_{0.78}\)Ge\(_{0.22}\) buffers, on a Si\(_{0.72}\)Ge\(_{0.28}\) virtual substrate. In the first sample (SQW2) the active layers were strain symmetrized on top of strain-relaxed nominally Si\(_{0.78}\)Ge\(_{0.22}\) buffers which involved growth of a \( \sim 3 \mu \text{m} \)-thick linearly graded Si\(_{1-x}\)Ge\(_{x}\) buffer followed by \( \sim 1 \mu \text{m} \) of Si\(_{0.78}\)Ge\(_{0.22}\). Above the strain-relaxation buffer, ten periods of 5 nm \( p \)-Si\(_{0.78}\)Ge\(_{0.22}\) \( (N_A = 5 \times 10^{17} \, \text{cm}^{-3} \, \text{B}) \), 2.8 nm \( i \)-Si\(_{0.78}\)Ge\(_{0.22}\) spacer, 5.3 nm \( i \)-Si barrier, 12 nm \( i \)-Si\(_{0.72}\)Ge\(_{0.28}\) quantum well, 5.3 nm \( i \)-Si barrier, 2.8 nm \( i \)-Si\(_{0.78}\)Ge\(_{0.22}\) spacer, and 5 nm \( p \)-Si\(_{0.78}\)Ge\(_{0.22}\) was grown. The wafer was capped with 100 nm Si\(_{0.78}\)Ge\(_{0.22}\), 10 nm \( p \)-Si\(_{0.78}\)Ge\(_{0.22}\), and 4.5 nm \( i \)-Si to reduce band bending at the surface. Layer thicknesses were measured by transmission electron microscopy, and the Ge mole fractions found by energy dispersive x-ray spectroscopy. In a second sample (SQW3) the structure comprised ten modulation doped, strain balanced Si\(_{0.75}\)Ge\(_{0.25}\) quantum wells with Si barriers, grown on a Si\(_{0.8}\)Ge\(_{0.2}\) virtual substrate, and separated by Si\(_{0.8}\)Ge\(_{0.2}\) spacer regions.

The pump-probe measurements of nonradiative intersubband relaxation were made with FELIX in the temperature range 4–100 K. A three-beam balanced pump-probe technique described earlier\(^4\) was used in the FIR region of interest. The macropulse duration was 5 \( \mu \)s with 5 Hz repetition rate. The macropulse contained a train of micropulses of \( \sim 3 \) ps duration and 25 MHz repetition rate. A polarization rotator was used to change the polarization of the pump to be perpendicular to the probe, hence eliminating any so-called “coherence artifact” effect. Beyond the sample an analyzer was placed to eliminate the scattered pump radiation from the detector.

\(^{4}\)Electronic mail: c.r.pidgeon@hw.ac.uk
Measurements between 4 and 100 K were carried out at different angles of incidence, enabling access to both \( LH1-HH1 \) and \( HH2-HH1 \) transitions, in order to maximize the induced probe transmission signal change. The pump was set on the intersubband transition wavelength, obtained both from Fourier transform infrared (FTIR) transmission spectra and by maximizing the pump-probe transmission step. Degenerate pump-probe transmission spectra (i.e., differential probe transmission as a function of delay behind the bleaching pump pulse) are shown in Fig. 1 at 45 \( \mu \)m, in the temperature range 4–80 K, for one of the two prototype structures measured (sample SQW2). In this case, in order to maximize the signal, the sample was set at an angle of 45°, accessing predominately \( HH2-HH1 \) transitions. But we note that the \( HH2-HH1 \) and \( LH1-HH1 \) transitions cannot be spectrally resolved for our structures at these long wavelengths, and must be distinguished by the experimental geometry and associated optical selection rules (see later).

These results are consistent with our theoretical calculations. Both SQW2 and SQW3 have FIR absorbing states localized in the spacer layers, in the energy range between the \( HH1 \) and \( LH1 \) quantum-well states, which are responsible for the dual-decay transmission response. The sharp feature with an exponential decay time of 10 ps, that remains at all temperatures, is associated with intersubband relaxation within the well. The slow subsequent rise and then fall of transmission, which occurs at low temperatures only, is associated with scattering into intermediate states confined in the spacer layers. Similar results were obtained on the second sample (SQW3), as shown in Fig. 2. The figures show the effect of both temperature and pump beam intensity on the transmission response, indicating the striking result that the sharp feature is relatively independent of both lattice and electron temperature. Finally, pump-probe experiments were performed on SQW2 for a range of pump wavelengths, confirming the resonance with the intersubband transition.

Electroluminescence emission spectra were previously obtained at both normal incidence (\( LH1-HH1 \) transitions) and in-plane (predominately \( HH2-HH1 \) transitions) by step-scan FTIR spectroscopy utilizing phase sensitive detection, the latter being observed only in 1M polarization as expected. A periodic signal consisting of a train of square pulses with a 50% duty cycle and at a frequency of 418 Hz was injected into the sample, with the voltage drop in the plane of the quantum wells. FTIR spectra of the intersubband absorption were measured at the same time, in both configurations. A broad (full width at half maximum=15 meV) feature was observed centered on 28 and 24 meV for SQW2 and SQW3, respectively, in good agreement with our \( k \)-\( p \) calculations at these long wavelengths. Figure 3 shows the calculated energy minima for subbands up to quantum number 3 which are confined in the wells, and also for a further set of subbands which are confined in the unstrained SiGe spacer layers separating adjacent wells.

Calculations of intersubband relaxation rates due to phonon scattering by acoustic and the three optical phonon modes (Ge–Ge, Ge–Si, Si–Si), and due to alloy disorder scattering were performed for both \( LH1-HH1 \) and \( HH2-HH1 \) transitions with the fully anisotropic subband structure, obtained using the \( 6 \times 6 \) \( k \)-\( p \) method.\(^5\)\(^6\) The intersubband alloy scattering rates were calculated for a range of values of the alloy scattering potential \( U_0 \) reported in the literature,\(^7\) and the best agreement with our pump-probe experiments (later) was obtained with \( U_0=0.3 \) eV normalized to the primitive unit cell volume.\(^5\)\(^7\) It is found that in...
In conclusion, intersubband relaxation in two strain-symmetrized $p$-Si/SiGe multiple quantum-well samples, both with subband energy separations less than the Si and Ge phonon energies, is found to be approximately constant in the temperature 4–100 K. The results are in good agreement with theoretical predictions, which indicate that intersubband alloy disorder scattering (which is almost temperature independent) is dominant in such structures throughout this temperature range. The intersubband lifetimes were also found to be insensitive to the FELIX pump power. These conclusions are in sharp contrast to similar measurements made by us on the GaAs/AlGaAs system in which polar optical phonon scattering dominates, giving a strong dependence of subband lifetime on both temperature and excitation level.8,9

This Si/SiGe program is funded by DARPA on the USAF Contract No. F-19628-99-C-0074. The authors are grateful to EPSRC (UK) for support as part of the UK program at FELIX and are grateful for the skillful assistance of Dr. A. F. G. van der Meer.