n-type Ge/SiGe Multi Quantum-Wells for a THz Quantum Cascade Laser

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Exploiting intersubband transitions in Ge/SiGe quantum cascade devices provides a way to integrate terahertz light emitters into silicon-based technology. With the view to realizing a Ge/SiGe Quantum Cascade Laser, we present the optical and structural properties of n-type strain-symmetrized Ge/SiGe asymmetric coupled quantum wells grown on Si(001) substrates by means of ultrahigh vacuum chemical vapor deposition. We demonstrate high material quality of strain-symmetrized structures and heterointerfaces as well as control over inter-well coupling and electron tunneling. Motivated by the promising results obtained on ACQWs, which are the basic building block of a cascade structure, we investigate, both experimentally and theoretically, a Ge/SiGe THz QCL design, optimized through a non-equilibrium Green's function formalism.

Introduction

Terahertz (THz) quantum cascade lasers (QCLs) have been demonstrated with different III-V materials (1). In the past decade however, relatively small progress has been reported to increase the maximum operating temperature (presently 200 K) despite substantial efforts of design optimization. The rationale for the quenching of THz laser emission above this temperature is due to the very effective electron–phonon (e–phonon) interaction, typical of III-V materials. Indeed, in polar lattices the longitudinal optical (LO) phonons induce a long-range polarization field which strongly couples to the charge carriers (Fröhlich interaction). The THz transitions are typically designed to be well below the optical phonon energy (30–36 meV), so that at low temperature the upper laser state is protected against scattering by emission of LO-phonons. With increasing temperature however, the thermally activated electrons in the subband of the upper lasing state gain enough in-plane kinetic energy to access this scattering channel. This non-radiative relaxation of carriers reduces the population inversion and is responsible for quenching of the laser emission with increasing temperature as the gain drops below the cavity losses. As an alternative strategy, non-polar material systems are attractive because of their weaker e–phonon interaction. Indeed, in these crystals the e–phonon coupling is controlled by the deformation potential which due to its short range is much less effective than the Fröhlich interaction. Among different configurations (electron or hole based, Si or Ge rich regimes), theoretical studies have indicated n-type Ge/SiGe heterostructures where charge transport is associated to L electrons, as the most promising architecture (2). Experimentally, sharp THz absorption peaks, related to intersubband transitions in n-type strain compensated Ge/SiGe quantum wells (QWs) have been demonstrated in the 20–50 meV region (3,4) which interestingly covers the Reststrahlen band of III-V compounds.

Results

With the view to realizing a Ge/SiGe QCL, we present the optical and structural properties of n-type strain-symmetrized Ge/SiGe asymmetric coupled quantum wells (ACQWs) grown on Si(001) substrates by means of ultrahigh vacuum chemical vapor deposition (5).

Extensive structural characterization obtained by scanning transmission electron microscopy (STEM), atomic probe tomography (APT) and X-ray diffraction shows the high material quality of strain-symmetrized structures (up to 5-micron active region thickness) and heterointerfaces (featuring interface roughness below 0.2 nm), down to the ultrathin barrier limit (about 1 nm) (Fig. 1).

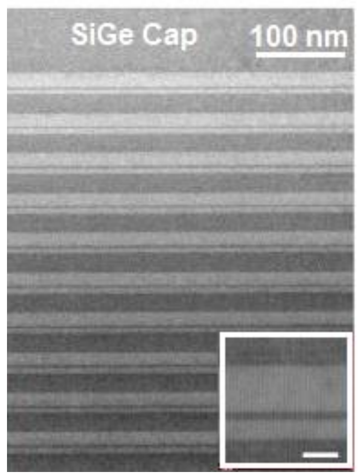

Figure 1. Z-contrast STEM image of an ACQW sample having a barrier thickness of 2.3 nm. The inset shows a single period of the structure (scale bar =10 nm).

By performing Fourier Transform Infrared (FTIR) absorption spectroscopy measurements on different ACQWs (varying well width or barrier thickness (Fig. 2)), we could identify two intersubband (ISB) absorptions, E_{01}^{abs} and E^{02abs}, due to transitions from ground level respectively to the first- and second-excited level of the ACQW system, and unambiguously demonstrate control over inter-well coupling and electron tunneling (5). These results combined with the modeling of non-radiative lifetimes measured by pump-probe experiments allowed us to evaluate the key parameters driving electron scattering in the SiGe material system.

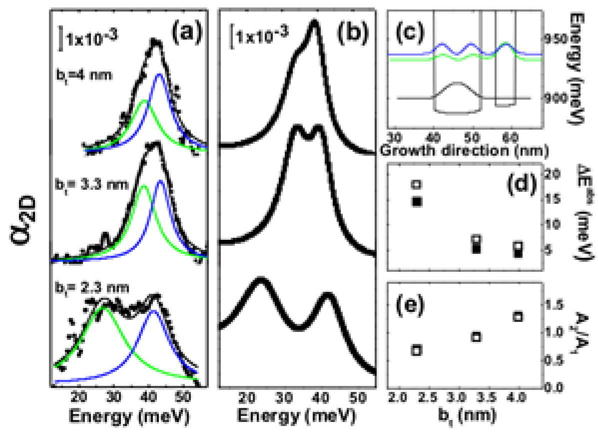

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Figure 2: Dots: experimental ISB absorption spectra measured by FTIR on ACQWs as a function of the tunneling barrier width (b_t) at fixed well widths of 12 and 5 nm. (b) Corresponding calculated spectra. (c) Calculated squared wavefunctions for b_t= 4 nm. Energy difference E02abs-E01abs (d) and ratio of the integrated spectral weight of the two ISB absorption peaks (e) plotted vs b_t.. Closed (open) symbols are used for experimental (numerical) data

To assess the potential of this material system as a gain medium for intersubband cascade devices, we used the non-equilibrium Green's function formalism to benchmark a Ge/SiGe 4-quantum well QCL against a GaAs/AlGaAs counterpart whose conduction band edge profiles and electronic states are reported in Fig. 3 (6).

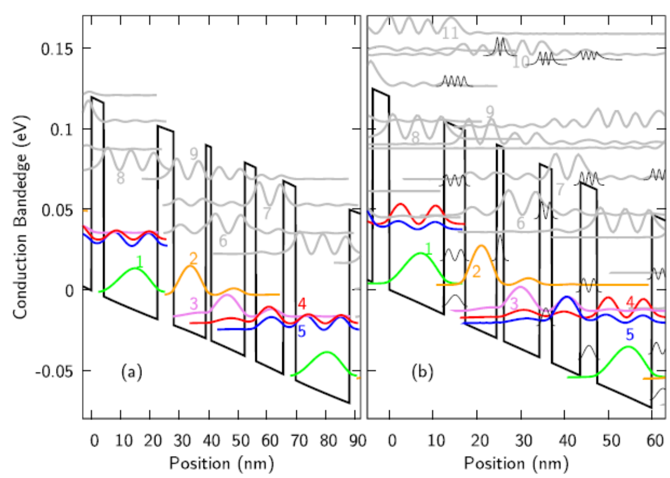

Figure 3: The conduction band profile and electronic states (squared modulus) fo the four-well GaAs/$Al_{0.15}Ga_{0.85}As$ (a) and Ge/$Si_{0.23}Ge_{0.77}$ (b) QCL design calculated for the applied electric fields of 7.9 and 12.0 kV/cm, respectively. The electronic states shown are solutions of the Schroedinger equation on a single period (tight-binding basis). In panel (b),Δ_2 states confined in the barriers are also shown (dark grey lines). Simulations show that, due to the non-polar nature of SiGe alloys, the maximum gain of a Ge/SiGe QCL is much more robust against the temperature increase with respect to III-V based devices. Moreover, the interface roughness values measured on our samples are predicted to allow the possibility to achieve gain overcoming the losses of optimized double-metal waveguides at room temperature.

Strain compensated QCL structure having an active region of several microns were grown and fabricated to mesa devices with top diffraction gratings to measure the surface emission under bias. FTIR spectra measured at 9K show a well-defined peak at 8-9 meV with a FWHM of roughly 4 meV that could indicate electroluminescence from intersubband transitions.

Acknowledgment

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