Light from Silicon: SiGe Quantum Cascade Structures

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Recently, encouraging results on electroluminescence of valence band SiGe cascade structures in the mid- and far infrared (THz) spectral regions have been reported. In this paper, we review these results an compare them to **kp** bandstructure calculations based on a strain dependent Luttinger Kohn Hamiltonian.

Introduction

The working principle of a quantum cascade (QC) emitter is based on optical transitions of only one type of carrier (uni-polar emitter). Typically, one period of the cascade consists of an active region and of an injector region. The active region is built up of typically 1 – 4 quantum wells (QW) that are designed for intense emission at the target wavelength, for long non-radiative life time in the excited state of the laser transition and for efficient depopulation of the laser-transition ground-state. The injector consists of a chirped superlattice in that the ground states of adjacent QWs become aligned in energy for a certain voltage drop across the cascade period. At this voltage, an energetically flat miniband is formed in the injector superlattice through that the carriers coherently tunnel from the ground state of the active region to the excited state of the active region of the following cascade period. (For an illustration of the QC principle, see for example [1].) Up to now, quantum cascade lasing has been demonstrated only in structures made from III-V materials. In these systems, the quantum cascades are formed in the conduction band.

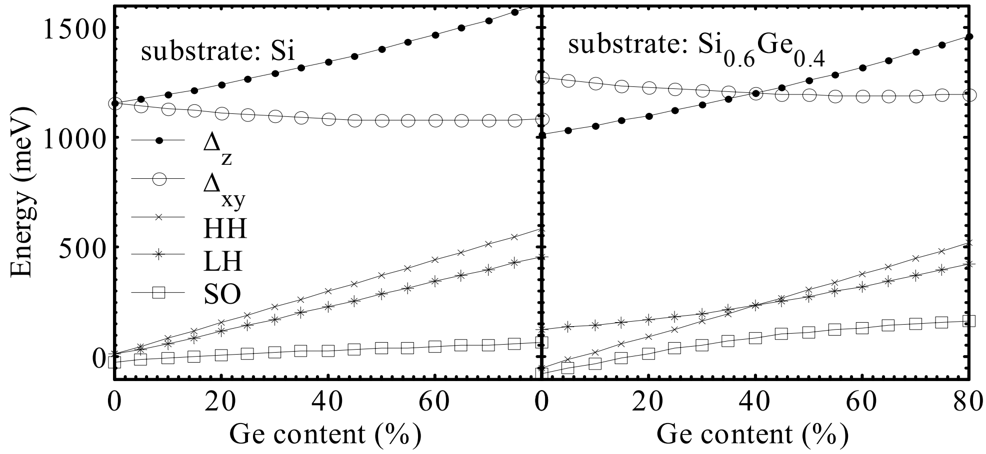

Fig. 1: Calculated band line-up for pseudomorphic SiGe alloys grown on a Si substrate (left panel) and a $Si_{0.6}Ge_{0.4}$.pseudo-substrate (right panel).

Since no optical transitions over the fundamental band gap are involved in the emission process of a quantum cascade device, the QC concept is a promising strategy to achieve light emission also in indirect fundamental band-gap materials like Si and Ge. For the Si/Ge material system, the calculated alignment of the conduction and valence band edges as a function of the SiGe alloy composition is shown in Fig.1. for growth on a Si (left panel) and a $Si_{0.6}Ge_{0.4}$ (right panel) substrate. In the calculations, the parameters given in [2] were used. Due to the uniaxial strain in the epitaxial SiGe layer, the heavy (HH) and light (LH) hole valence band maxima as well as the Δ_{xy} and Δ_z conduction band minima become split. Figure 1 shows that holes are always confined to the Ge rich layers for both types of substrates. The ground states in the valence band QW are HH states, the HH band offset increases by approx. 70 meV per 10% of Ge in the alloy. For electrons, nearly no band offset occurs in the conduction band for growth of SiGe alloys on a Si substrate. For SiGe epitaxy on SiGe substrates, QW are formed in the conduction band of the Si rich layers. The ground states of these QWs are built up from the Δ-valleys in the growth direction. However, the electrons in these valleys have a huge effective mass (0.98 m_0) in the direction of the confinement so the coupling of neighboring QWs is extremely weak. Therefore, all of the work on light emission of SiGe cascades published so far has been performed on valence band QWs.

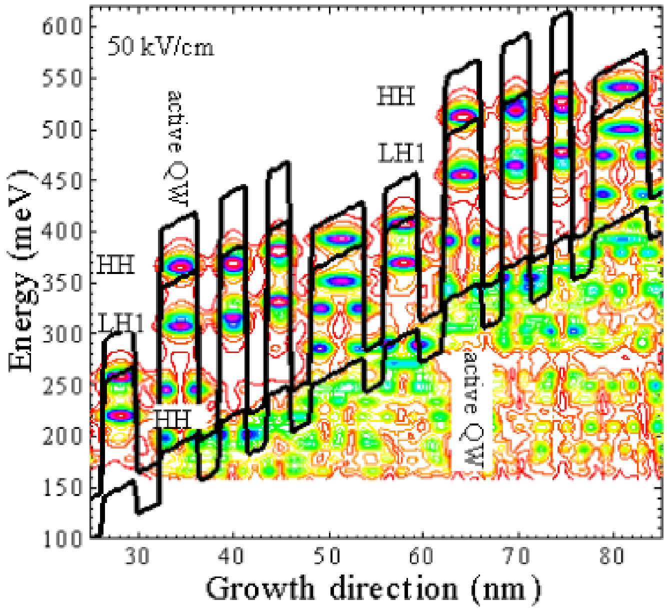

Fig. 2: Valence band potentials, eigenstates and hole wave functions for a typical QC structure grown on Si substrate. The details of the plot are described in the text.

Experimental Results

Mid-Infrared Emission

Cascade light emission in the mid-infrared spectral region around 150 meV has been reported recently [3] – [6]. In Fig. 2, the band structure of a typical Si/SiGe cascade structure [3] calculated according to [2] is shown. The alignment of the HH, LH and split off (SO) hole bands edges are indicated by the dashed, full and dashed-doted lines, respectively. The moduli of the wave functions are plotted as contour lines centered around their eigenenergy. The broadening of the contours along the energy axis indicates the broadening of the eigenenergies (assumed to be 5 meV FWHM in the calculations). The emission wavelength is determined by the energy difference between the HH1 and HH2 in the QW labeled “active QW” in Fig. 2. From the HH1 state in the active QW, the holes tunnel via the HH groundstates in the neighboring QWs into the HH2 state of the next active QW.

Unlike in the case of cascade structures in the conduction band, in the valence band additional states exist between the HH2 and the HH1 states. These states are the ground states confined to QWs formed by the LH valence bands (labeled LH1 in Fig. 2). Pump and probe experiments have shown that the holes in the HH2 states are efficiently scattered into the LH 1 states by optical phonon deformation potential interaction reducing the hole life time in the HH2 state to approximately 250 fs [7]. Reducing the LH1-HH2 energy difference by a proper design of the active QW below the energy of an optical phonon blocks this recombination channel and enhances the power efficiency of the QC emission by approximately a factor 100 [3].

The growth of sophisticated cascade structures on Si substrates is limited by the accumulated strain energy in the epitaxial SiGe layers. These limitations can be overcome by growth on SiGe virtual substrates: Intersubband absorption of high quality $Si_{0.2}Ge_{0.8}$ QWs on a $Si_{0.5}Ge_{0.5}$ virtual substrate [8] as well as electroluminescence around 175 meV due to a bound-to-miniband transition in a QC structure consisting of up to 30 cascades each containing 14 $Si_{0.2}Ge_{0.8}$ QWs separated by Si barriers grown on a $Si_{0.5}$ $Ge_{0.5}$ virtual substrate [6] were observed recently.

THz Emission

In the THz region, up to now no emission from typical cascades containing an injector and active QW region has been published. However, THz emission from $Si_{0.72}Ge_{0.28}$ multi-QWs separated by Si barriers grown on a $Si_{0.77}$ $Ge_{0.23}$ virtual substrate has been observed [9] under an electrical field parallel to the growth direction. For this sample, the in-plane dispersions in [100] direction of the four hole states within the energy range of the experiments are plotted in Fig. 3.

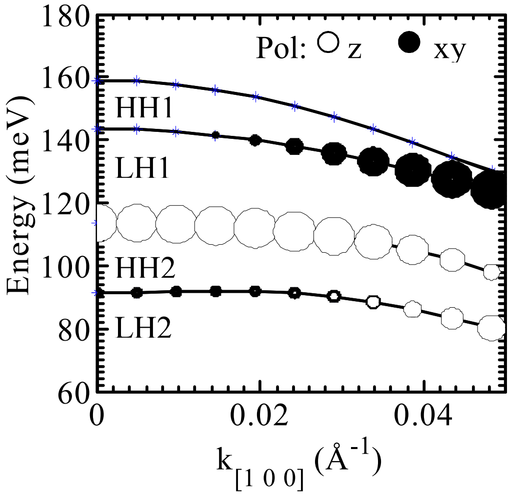

Fig. 3: In-plane dispersion along [100] direction for a $Si_{0.72}Ge_{0.28}$ QW on a $Si_{0.77}$ $Ge_{0.23}$ virtual substrate. The diameters of the symbols indicate the relative size of the optical dipol matrix element for transitions to the HH1 ground state. The open (full) symbols refer to light polarized parallel to z (xy) direction (growth direction: z).

The diameter of the open (full) symbols in Fig. 3 indicates the magnitude of the matrix-element for optical dipole transitions in z (xy) polarization between the HH1 ground and the LH1, HH2, LH2 excited states. Experimentally, the HH1-LH1 as well as the HH1-HH2 emission bands have been observed close to the calculated transition energies (at 10 meV and 40 meV) with the polarization selection rules indicated in Fig. 3 [9]. For the LH2 emission band, the matrix element is calculated to be much smaller than for the LH1 and HH2 bands. Consequently, in the emission experiments, the signal was close to the noise level at the calculated transition energy around 65 meV. In [10], a power conversion efficiency in excess of that observed for III-V *electroluminescence* devices is reported.

Conclusion

Both in the MIR and THz regime encouraging results have been obtained from electroluminescence experiments. While for the samples emitting in the MIR range, typical QC designs are employed, the samples for THz emission contain a series of uncoupled QWs. The experiments and model calculations indicate that in both spectral regions the realization of Si/Ge based QC lasers appears feasible.

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