Terahertz gain in a SiGe/Si quantum staircase utilizing the heavy-hole inverted effective mass

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Citation: Appl. Phys. Lett. 79, 3639 (2001); doi: 10.1063/1.1421079
View online: http://dx.doi.org/10.1063/1.1421079
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Previous work on electrically injected SiGe/Si quantum-well (QW) THz lasers1–3 has centered on the light-hole-1 to heavy-hole-1 (LH1 to HH1) intersubband transition that is suitable for $XY$ polarized vertical-cavity surface emitting lasers. In this letter, we propose a hole-injected Z-polarized edge-emitting THz laser that employs the HH2 to HH1 transition, in which an inverted effective mass (IEM) is engineered for the HH2 subband near the zone center. Assuming an operating temperature of 77 K, we calculate the well-and-barrier parameters that yield the HH2 IEM, a local band dispersion in $(k_x, k_y)$ space, wave function amplitudes, and band mixing among HH, LH, and SO using the $6 \times 6$ band $k \cdot p$ commercial software from Quantum Semiconductor Algorithms, Inc., Northborough, MA. The software includes strain effects and it uses a 0.68 eV Ge/Si valence band offset.

The IEM exists over several regions in $x, l_w, l_b$ space. For example, using the SL boundary condition at $q_z = 0.5$, $F = 0$, $x = 0.3$, and keeping $l_b$ fixed at 40 Å, we find a LH1 IEM when 98 Å < $l_w$ < 105 Å. An increase in $l_w$ produces a HH2 IEM over the range of 105 Å < $l_w$ < 112 Å. Increasing $l_w$ to more than 112 Å leads to quasiparabolic HH2 dispersion. The changeover from the LH1 IEM to the HH2 IEM as $l_w$ widens is general behavior. The quasiparabolic $F_0$-biased HH2 structures appear to be feasible for QSLs, but at higher-$J$ thresholds than IEM SLs.

The SiGe/Si superlattice (SL) is assumed to be strain balanced, that is, the compressively strained Si$_{1-x}$Ge$_x$ QW layers and the tensile strained Si barrier layers are grown on a relaxed Si$_{1-x}$Ge$_x$ buffer layer-on-(100) Si (a virtual substrate), where $y$ is chosen to give zero net strain for the specific $x$, $l_w$, and $l_b$ being studied ($l_w$ = QW thickness, $l_b$ = barrier thickness). For SLs with (or without) an electric field applied, we determined the subband energies, subband dispersion in $(k_x, k_y)$ space, wave function amplitudes, and band mixing among HH, LH, and SO using the $6 \times 6$ band $k \cdot p$ commercial software from Quantum Semiconductor Algorithms, Inc., Northborough, MA. The software includes strain effects and it uses a 0.68 eV Ge/Si valence band offset. The IEM exists over several regions in $x, l_w, l_b$ space. For example, using the SL boundary condition at $q_z = 0.5$, $F = 0$, $x = 0.3$, and keeping $l_b$ fixed at 40 Å, we find a LH1 IEM when 98 Å < $l_w$ < 105 Å. An increase in $l_w$ produces a HH2 IEM over the range of 105 Å < $l_w$ < 112 Å. Increasing $l_w$ to more than 112 Å leads to quasiparabolic HH2 dispersion. The changeover from the LH1 IEM to the HH2 IEM as $l_w$ widens is general behavior. The quasiparabolic $F_0$-biased HH2 structures appear to be feasible for QSLs, but at higher-$J$ thresholds than IEM SLs.

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We want to eliminate optical phonon emission from the upper laser state and make the radiative-to-nonradiative branching ratio as large as possible. Since the QWs contain Si–Si, Si–Ge and Ge–Ge lattice vibration modes (with optical phonon energy $\hbar \omega_0 = 64.5, 50.8$ and $37.2$ meV, respectively), we engineer the SL so that the laser photon energy ($\hbar \omega_j$) is less than the lowest-energy Ge–Ge phonons. This requires small values of $x$. We then analyze a model system consisting of two QWs under electric field bias, knowing that the easily computed two-well results for the lowest-two HH consist of two QWs under electric field bias, knowing that $N$ large than the QSL cavity losses such as free carrier absorption.

The total concentration $N$ of holes injected into the doublets is $N = N_1 + N_2$, and when quasiequilibrium is reached in the doublets, the Boltzmann relation gives $N_1 = N_2 \exp (-\delta E/kT)$, where $\delta E$ is the $3$ meV energy separation within the doublets. This relation holds for all doublets. Also, the injected current density can be related to the total population as $J = eN/l_{\text{eff}}$, where $l_{\text{eff}}$ is the effective lifetime $1/l_{\text{eff}} = 1/l_{\text{sp}} + 1/l_{\text{ph}}$, in which $l_{\text{sp}}$ is the spontaneous emission lifetime in the Fig. 3 level-3-to-level-2 laser transition, and $l_{\text{ph}}$ is the nonradiative lifetime on that transition. In turn, $l_{\text{ph}}$ is governed by the hole-acoustic-phonon scattering rate, which we have determined for the Fig. 1 QW using the formalism given by in Sun et al. Our calculations give $l_{\text{ph}} = 1.0$ ns.

The dipole matrix element of the vertical in $k$ space lasing transition is the overlap integral between two HH wave functions (upper and lower laser states) which, according to Fig. 2, are localized in the same QW. We performed this integration numerically and found that $\langle \text{HH}_1 | e | \text{HH}_2 \rangle = 20$ Å in Fig. 2. This result in turn implies that $l_{\text{sp}} = 77$ μs. We used these two lifetimes together with the Boltzmann distributions to estimate hole populations, which showed a total inversion of the Fig. 3 HH2(n) population relative to HH1(n), as desired. Finally, with the aid of Eq. (5) in Ref. 3, we estimated the gain as a function of $J$ with the result presented in Fig. 4. The peak gain of 450 cm$^{-1}$ at 7.3 THz is expected to be larger than the QSL cavity losses such as free carrier absorption.

In conclusion, we have designed and simulated a $3–9$ THz, $77$ K strain-balanced Z-polarized SiGe/Si $p$–$i$–$p$ laser in a simplified form of the quantum staircase that we call the quantum staircase. The $x$, $l_a$, and $l_b$ are selected to give the IEM for HH2, which optimizes the THz gain. The staircase is biased above the antireflecting field, creating two active HH doublets per QW, a four-level system. The first $p^+$ contact injects holes selectively into the doublets of the first QW, while the second $p^+$ contact collects holes from the doublets of the last QW in this high-gain superlattice.
The authors wish to acknowledge helpful discussions with Zoran Ikonic, Robert W. Kelsall, and Paul Harrison of the University of Leeds.