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Intersubband lasing lifetimes of SiGe/Si and GaAs/AlGaAs multiple quantum well structures

Greg Sun
University of Massachusetts Boston, greg.sun@umb.edu

L. Friedman
Air Force Research Laboratory, Hanscom Air Force Base

Richard A. Soref
Air Force Research Laboratory, Hanscom Air Force Base

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G. Sun, L. Friedman, and R. A. Soref

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Intersubband lasing lifetimes of SiGe/Si and GaAs/AlGaAs multiple quantum well structures

G. Sun
Engineering Program, University of Massachusetts at Boston, Boston, Massachusetts 02125

L. Friedman and R. A. Soref
Rome Laboratory/EROC, Hanscom Air Force Base, Hanscom, Massachusetts 01731-2909

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The feasibility of population inversion is studied for the SiGe/Si system and compared with that of GaAs/AlGaAs. Because of the absence of strong polar optical phonon scattering in SiGe/Si, the lifetime difference of the upper and lower lasing levels, to which the population inversion and laser gain are proportional, is consistently an order of magnitude larger than that of GaAs/AlGaAs; nor does it show the sudden drop to zero or negative values when the lasing energy exceeds the optical phonon energy. Both systems studied are superlattices, each period of which consists of three coupled quantum wells and barriers.

For the III-V semiconductors, population inversion and lasing due to intersubband transitions have been predicted for the GaAs/AlGaAs superlattice[1] and demonstrated in a InGaAs/AlInAs structure.[2] Population inversion and laser gain of an intersubband laser depends on the difference in lifetimes of the upper and lower lasing levels, and these can be optimized by band-gap engineering of the well and barrier thicknesses. In the III-V materials, the lifetimes are limited by strong LO polar optical phonon scattering. Thus, one is restricted to lasing energies less than the optical phonon energy $\hbar\omega_0$ in order to suppress phonon scattering,[1] although some lifetime increase occurs at large energies, as discussed below.

The purpose of this letter is to point out that the absence of strong polar optical scattering in silicon-based materials results in considerably longer lifetimes than in the III-V semiconductors. We will show that with only nonpolar optical phonon and acoustic phonon scattering operatives, not only are the lifetimes considerably longer, but they do not show the sharp reduction when the laser transition energy exceeds the optical phonon threshold energy. Both Ge_xSi_{1-x}/Si and $GaAs/Al_yGa_{1-y}As$ superlattices are considered. Because of the very different effective masses and band offsets of the two systems, the well and barrier widths will differ considerably, but the same coupled-quantum-well structure and treatment is used for both cases.

To focus only on the issue of the lifetimes, we consider a minimal configuration consisting of a superlattice, each period of which has three $Ge_{0.25}Si_{0.75}$ quantum wells (QWs) and three Si barriers of different widths. Figure 1 shows the heavy hole valence band diagram. Each QW is designed so that there exists only one confined state when isolated. The three QWs form a three level system with three subbands (actually minibands of very small width) within the HH valence band. Taking levels 2 and 3 of Fig. 1 as the lower and upper laser states, respectively, neglecting carrier scattering from the ground state and thermal excitation, and assuming optical pumping, it can be shown that the population inversion is given by

$$N_3-N_2=N_1\sigma_{31}(I_p/\hbar\omega_p)(\tau_3-\tau_2), \tag{1}$$

where I_p is the pump power density, the absorption cross section

$$\sigma_{31}=(4\pi\alpha_0/n_0)(\hbar\omega_p/\Gamma)|\langle 3|z|1\rangle|^2, \tag{2}$$

with N_i ($i=1,2,3$) the population of subband i, τ_i the lifetime of subband i, α_0 the fine structure constant, n_0 the refractive index, $\langle 3|z|1\rangle$ the dipole matrix element, Γ the linewidth, and $\hbar\omega_p=E_3-E_1$ the pump energy. It is therefore essential for the lasing operation to achieve a large lifetime difference.

The laser gain at frequency ω_L is

$$G_L=\sigma_{21}(N_3-N_2), \tag{3}$$

where σ_{21} is given by Eq. (2) above with 3 replaced by 2 and $\hbar\omega_p$ replaced by $\hbar\omega_L=E_3-E_2$. Since we focus here on the lifetime difference, the pumping mechanism is not important and will be addressed at a later time.

The lifetime τ_i of subband i is $\tau_i=[\Sigma_j(W^a_{ij}+W^0_{ij})]^{-1}$, where

$$W^a_{ij}=(\Xi^2_d k_B T^*_m/4\pi c_L\hbar^3)\int|G_{ij}(q_z)|^2 dq_z \tag{4}$$

for acoustic phonon scattering,[3] with Ξ_d the valence band deformation potential, m^* the heavy hole effective mass, c_L

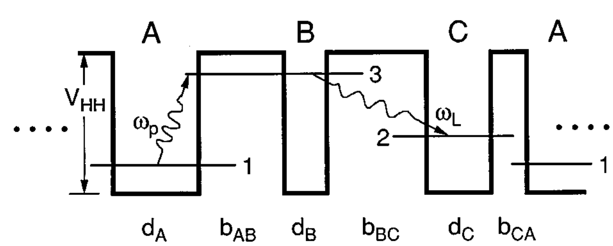

FIG. 1. One period of heavy-hole valence band diagram of superlattice. Hole energy increases in the upward direction. V_{HH} is the heavy-hole valence band offset. Indicated are well and barrier widths, subband levels, and pump(p) and lasing (L) transitions.

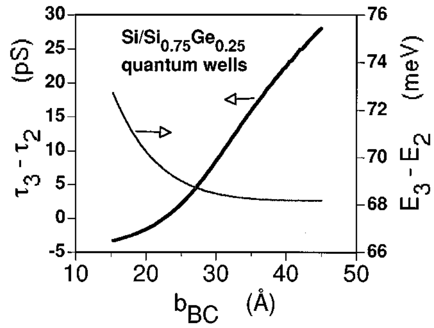

FIG. 2. Lifetime difference $(\tau_3-\tau_2)$ and subband energy difference (E_3-E_2) as a function of barrier width b_{BC}.

the elastic constant, k_B Boltzmann's constant, T the absolute temperature, taken to be room temperature, and q_z the phonon wavevector in the growth direction. (i, j) are subband labels.

For nonpolar optical phonon scattering,[3]

$$W_{ij}^0 = m^*[n(\omega_0)+1/2\mp 1/2]D_0^2/4\pi\rho\hbar^2\omega_0 \times \int |G_{ij}(q_z)|^2 dq_z, \quad (5)$$

where $n(\omega_0)=1/[\exp(\hbar\omega_0/k_BT)-1]$ is the phonon population of frequency ω_0 (assumed constant), D_0 is the valence band optical deformation potential, and ρ is the mass density. For the GaAs/AlGaAs system, the Frohlich interaction[3] for polar optical scattering was used in addition to acoustic phonon scattering.

In both Eqs. (4) and (5),

$$G_{ij}(q_z)=\langle i|\exp(iq_z z)|j\rangle \quad (6)$$

contains wave-function overlap effects, and $\int|G_{ij}(q_z)|^2dq_z$ has to be calculated numerically. Thus, from Eqs. (4) and (5), it is seen that the intersubband scattering rates depend on the wave-function overlap between the two subbands involved. In general, this decreases with increasing width of the barrier separating the two subbands. As a result, we are able to manipulate the lifetimes of all the subbands to favor population inversion.

The parameters[4] in Eqs. (4) and (5) are Ξ_d(Ge) $=a=2.6$ eV, $m^*/m_0(\mathrm{Si})=0.291$, $m^*/m_0(\mathrm{Ge_{0.25}Si_{0.75}})=0.264$, $\rho(\mathrm{Ge_{0.25}Si_{0.75}})=3.07$ g/cm^3, $c_L(\mathrm{Si})=1.655\times10^{11}$ N/m^2, $c_L(\mathrm{Ge})=1.29\times10^{11}$ N/m^2, $D_0(\mathrm{Ge})=8.7\times10^8$ eV/cm, $\hbar\omega_0$ $(\mathrm{Ge_{0.25}Si_{0.75}})=56$ meV, and $V_{\mathrm{HH}}=205$ meV (see Fig. 1). Figure 2 shows the lifetime difference $(\tau_3-\tau_2)$ and subband energy difference (E_3-E_2) for the $\mathrm{Ge}_x\mathrm{Si}_{1-x}$/Si superlattice as a function of the barrier width b_{BC} separating the narrowest and intermediate-width wells associated with the two lasing states. While (E_3-E_2) is negligibly affected, $(\tau_3-\tau_2)$ increases from negative values to about 30 ps as b_{BC} increases from 15 to 45 Å. Note that population inversion is possible in the $\mathrm{Ge}_x\mathrm{Si}_{1-x}$/Si superlattices even when (E_3-E_2) exceeds the optical phonon energy; this is in contrast to the GaAs/AlGaAs superlattice.[1] Figure 3 shows $(\tau_3-\tau_2)$ for both the $\mathrm{Ge}_x\mathrm{Si}_{1-x}$/Si and $\mathrm{GaAs/Al}_y\mathrm{Ga}_{1-y}\mathrm{As}$ systems as a function of (E_3-E_2). For the $\mathrm{GaAs/Al}_y\mathrm{Ga}_{1-y}\mathrm{As}$ conduction band, $y=0.3$, $V_0=300$ meV, $\hbar\omega_0=36$ meV, $\Xi_d=8.6$ eV, $m^*/m_0=0.067$, $c_L=1.18\times10^{11}$ N/m^2, $\epsilon_s=13.2$, and $\epsilon_\infty=10.9$. (E_3-E_2) was varied by changing d_C, which primarily controls E_2 (see Fig. 1). The well and barrier dimensions are given in the caption of Fig. 3. It is seen that $(\tau_3-\tau_2)$ for the $\mathrm{Ge}_x\mathrm{Si}_{1-x}$/Si system is consistently larger than that of $\mathrm{GaAs/Al}_y\mathrm{Ga}_{1-y}\mathrm{As}$.

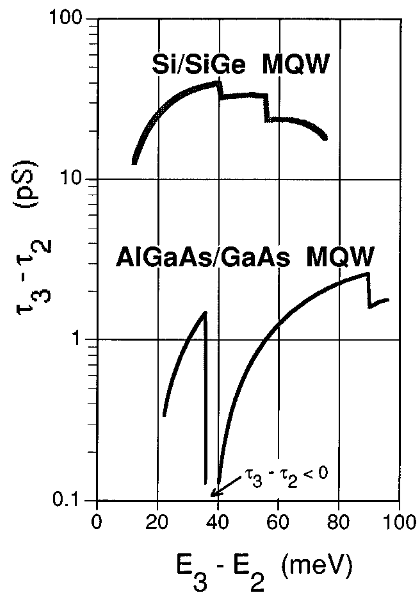

FIG. 3. Lifetime difference $(\tau_3-\tau_2)$ for both the GeSi/Si and GaAs/AlGaAs superlattices as a function of the lasing energy (E_3-E_2). For the $\mathrm{Ge_{0.25}Si_{0.75}}$/Si structure, $d_A=30$ Å, $b_{AB}=40$ Å, $d_B=10$ Å, $b_{BC}=40$ Å, $b_{CA}=10$ Å, and $d_B<d_C<d_A$. For the $\mathrm{GaAs/Al_{0.3}Ga_{0.7}As}$ structure, $d_A=50$ Å, $b_{AB}=40$ Å, $d_B=20$ Å, $b_{BC}=40$ Å, $b_{CA}=20$ Å, and $d_B<d_C<d_A$.

Both systems experience two sudden drops in $(\tau_3-\tau_2)$. For the $\mathrm{Ge}_x\mathrm{Si}_{1-x}$/Si system, the first drop occurs when $(E_3-E_2)=41$ meV, where (E_2-E_1) becomes less than $\hbar\omega_0$, and τ_2 suddenly increases. The second drop occurs when $(E_3-E_2)>\hbar\omega_0$, causing τ_3 to decrease. For the GaAs/AlGaAs system, $\hbar\omega_0=36$ meV is smaller, so that the drops occur in the reverse order. Note that for the $\mathrm{Ge}_x\mathrm{Si}_{1-x}$/Si system, $(\tau_3-\tau_2)$ maintains fairly large positive values in spite of the drops. However, for the GaAs/AlGaAs system, the drops can lead to zero or even negative values of $(\tau_3-\tau_2)$ (loss of population inversion).[1] For this case, $(\tau_3-\tau_2)$ will increase somewhat with increasing (E_3-E_2) due to the involvement of large wave-vector polar optical phonons[2] and lasing is still possible; nevertheless, it remains considerably smaller than that of the $\mathrm{Ge}_x\mathrm{Si}_{1-x}$/Si system.

Assuming $\Gamma=10$ meV and $n_0=3.5$ for $\mathrm{Ge_{0.25}Si_{0.75}}$, Si, and GaAs, we find $z_{13}=1$ to 10 Å, $z_{23}=5$ to 15 Å, and σ_{13} and σ_{23} for the structures of Fig. 3 in the range of 15–50 (Å)^2, for both the $\mathrm{Ge_{0.25}Si_{0.75}}$/Si and GaAs/AlGaAs systems. For $x=0.25$, we have assumed bulk optical phonons. For larger x, there may be confinement of the Ge–Ge and Ge–Si modes, which we believe will only reduce the scattering rates. This will be investigated.

In summary, we have presented theoretical evidence that the SiGe/Si system has a significant advantage over GaAs/AlGaAs (and other III-V's) QW systems for infrared intersubband lasers. For the same laser frequency, the laser lifetime difference in $Ge_{0.25}Si_{0.75}$/Si is at least an order of magnitude larger than that of $Al_{0.3}Ga_{0.7}As$/GaAs for laser emission energies below and above the optical phonon energy.

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