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Valence intersubband lasers with inverted light-hole effective mass

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We propose a novel intersubband laser based on transition between the ground-state heavy-hole subband (HH1) and light-hole subband (LH1) in a **k**-space region where the light-hole effective mass is inverted. The laser structure can be electrically pumped with a simple quantum cascade scheme. Our calculation shows that with only a small fraction of the carrier population in the upper subband (LH1), it is possible to achieve population inversion between the two subbands locally in **K** space where the light-hole effective mass is inverted. Optical gain in excess of 150/cm can be achieved with a pumping current density on the order to 100 A/cm^2 at the temperature of liquid nitrogen. © *1998 American Institute of Physics.* [S0003-6951(98)02112-3]

The coherent light sources have covered the spectral range from the soft x-ray region to the far infrared. Meanwhile, development of microelectronics has pushed the frontier of electronic devices beyond the 100 GHz range. Here we propose a new kind of intersubband lasers that will potentially bridge the gap between the far infrared and GHz microwaves, specifically in the 100 GHz ~10 THz range. Rapid advance of epitaxial growth techniques has opened the possibility for the development of a fundamentally new type of the semiconductor devices based on transitions between the subbands in quantum wells (QWs) and superlattices. Using the method of band-gap engineering, it is possible to adjust the energy of intersubband transition over a wide range. Recent development of the conduction-band quantum cascade laser (QCL)[1] based on intersubband transitions in two-dimensional semiconductor QW structures is a promising step, but so far, it has not been operated at wavelengths longer than 15 μm. Since the momentum scattering time in semiconductors is less than 1 ps, the operation of 1 THz intersubband lasers would require obtaining stimulated emission from a line with a Q-factor less than one, which seems to be highly improbable. The proposed scheme of valence intersubband laser using the feature of inverted light-hole effective mass, on the other hand, can circumvent these problems and achieve lasing in the desired THz range with a much simplified design of isolated single QWs.

For all practical purpose, conduction subbands in QWs can be treated as discrete levels when the band nonparabolicity can be negligible. It is therefore necessary to have the whole population of the upper subband exceed that of the lower one in order to achieve optical gain. Since the relaxation rates between different subbands are determined by the same physical processes, a complex multiple QW structure needs to be designed to engineer the lifetimes of involved subbands, as pointed out in our earlier work.[2] The conventional band-to-band semiconductor laser, on the other hand, appears to be more attractive from the point of view of achieving population inversion because of the nature of its band dispersion. Clearly, the difference in band dispersion stipulates that electrons in the conduction band always tend to relax toward the bottom, while electrons in the valence band tend to stay away from the top of the valence band, so that their absorption spectrum does not overlap with the emission spectrum of electrons in the conduction band. The lifetime of the upper laser states near the bottom of the conduction band is determined by the much slower interband process, while that of lower laser states near the top of the valence band is determined by the much faster intraband process. Therefore, lasing threshold can be reached when the whole population of the upper conduction band is only a tiny fraction of that of the lower valence band. Such a desirable feature has been demonstrated to a lesser degree in a QCL based on local **k**-space population inversion without the total intersubband population inversion,[3] owing to the band nonparabolicity as discussed by a recent theoretical study for the QCL.[4] Here we propose a scheme of valence intersubband lasers in which we can significantly enhance this feature by engineering the dispersion of two valence subbands in a QW similar to that of conduction and valence bands, i.e., one of the subbands shall be electron-like and the other hole-like. In order to achieve this, one of the subbands shall have its effective mass inverted. Such inversion is a result of interaction between the subbands, which is much stronger in the valence band. Indeed, in the valence band of most diamond and zinc-blende semiconductors, light- and heavy-hole subbands usually anticross, and near the point of anticrossing, the light-hole effective mass becomes electron-like. The in-plane dispersion of valence subbands can be calculated using the Kane model.[5] Since in GaAs-based materials the Γ_8 coupling with Γ_6 bands is weak, the 8×8 Hamiltonian matrix in the $\mathbf{k}\cdot\mathbf{p}$ theory reduces to a 4×4 valence band matrix taking into account the coupling between heavy-hole and light-hole bands.[6] The anticrossing between subbands LH1 and HH2 is clearly demonstrated in Fig. 1 producing a shallow energy valley in the in-plane dispersion of subband LH1 for a well width of 70 Å.

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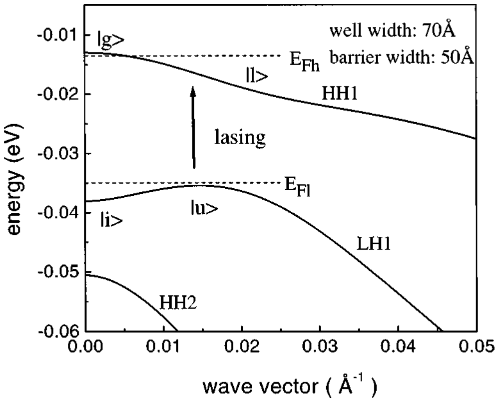

FIG. 1. In-plane dispersions of subbands HH1, LH1, and HH2 for a single QW with a well width of 70 Å. The hole energy is counted downward.

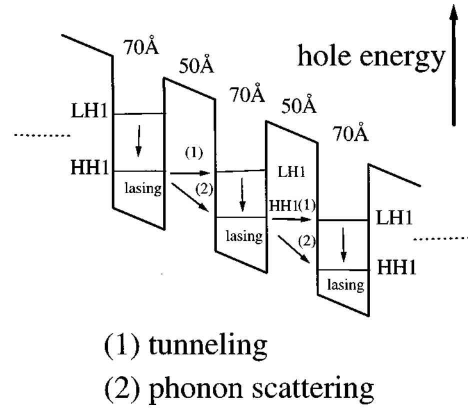

FIG. 2. A schematic of the quantum cascade scheme. The tunneling and phonon scattering processes have been identified as the mechanisms for pumping and current loss in the laser operation, respectively. The hole energy is counted upward.

If we now designate states near the Γ-point of subband LH1 as the intermediate states, $|i\rangle$, states near the valley (inverted-effective-mass region) of subband LH1 as the upper laser states, $|u\rangle$, states in subband HH1 vertically below the valley of subband LH1 as the lower laser states, $|l\rangle$, and states near the Γ point of subband HH1 as the ground states, $g\rangle$ (counting the hole energy downward), we can see that the situation closely resembles the one in the conventional band-to-band semiconductor laser. The upper and lower laser states can be quickly populated and depopulated through fast intrasubband processes, while the lifetime of upper laser states is determined by a much slower intersubband process between subbands LH1 and HH1. The inverted-effective-mass feature requires the coupled subbands to be closely spaced in energy. In a GaAs/AlGaAs QW, the energy separation between subbands HH1 and LH1 is typically less than the optical phonon energy (36 meV), which suppresses the nonradiative intersubband transitions due to the optical phonon scattering. Thus, near the inverted-effective-mass region in **k** space, the lifetime of upper laser states can be as long as a few nanoseconds, much longer than that of lower laser states on the order of picoseconds, $\tau_u > \tau_l$, a necessary condition for achieving population inversion between the laser states.

A quantum cascade scheme as shown in Fig. 2 is employed for electrical pumping between the two subbands, where carriers can tunnel from subband HH1 to LH1 in the next lasing cycle. We have estimated the tunneling time between subbands HH1 and LH1 to be $\tau_{\mathrm{tun}}=5$ ns for a barrier width of 50 Å taking into account the small tunneling probability between the heavy- and light-hole subbands. In competing with the tunneling process, the acoustic phonons can scatter carriers directly to the lower subband HH1 in the next laser cycle, resulting in current loss. The acoustic phonon process can have a much shorter scattering time of $\tau_{\mathrm{ph}} = 0.1$ ns at the liquid-nitrogen operating temperature of the laser.

Since the intrasubband process is significantly faster than the intersubband process, we can use quasi-Fermi levels (E_{Fl}, E_{Fh}) to describe light-hole and heavy-hole distributions in their respective subbands under a given pumping current density, $J_p = eNd(1/\tau_{\mathrm{tun}} + 1/\tau_{\mathrm{ph}})$, where e is the free electron charge, d is the well width, and N is the total hole population distributed between subbands LH1 (N_l) and HH1 (N_h) as

$$N=\sum_{k_i} \frac{k_i}{\pi d}[f_l(k_i)+f_h(k_i)]\Delta k_i, \tag{1}$$

where $k_i/\pi d$ is the density of states in **k** space for the interval of Δk_i at a given in-plane wave vector ($k_i=\sqrt{k_{i,x}^2+k_{i,y}^2}$), and $f_l(k_i)$ and $f_h(k_i)$ are Fermi–Dirac distribution for holes in subbands LH1 and HH1, respectively. A rate equation can be established for the population N_l of subband LH1,

$$\frac{\partial N_l}{\partial t}=\frac{N_h}{\tau_{\mathrm{tun}}}-\sum_{k_i} W_{\mathrm{ind}}(k_i)[f_l(k_i)-f_h(k_i)]\frac{k_i}{\pi d}\Delta k_i - \sum_{k_i} W_{\mathrm{spon}}(k_i) f_l(k_i)\frac{k_i}{\pi d}\Delta k_i \tag{2}$$

taking into account contributions from carrier tunneling, induced and spontaneous emissions. Since the energy separation between subbands HH1 and LH1 is below the optical phonon energy (36 meV) and the laser is designed to operate at the temperature of liquid nitrogen, the contributions from nonradiative intersubband acoustic phonon scattering and Auger processes are neglected in Eq. (2). The spontaneous emission rate is given by

$$W_{\mathrm{spon}}(k_i)=\frac{\tilde{n}e^2E(k_i)}{3\pi^2\epsilon_0 m_0^2 c^3\hbar^2}|M_p(k_i)|^2, \tag{3}$$

where $\hbar$ is the Planck constant, m_0 is the free-electron mass, ϵ_0 and c are the permittivity and light velocity in vacuum, $\tilde{n}$ is the index of refraction, $E(k_i)=E_l(k_i)-E_h(k_i)$ and $M_p(k_i)$ are the optical transition energy and momentum matrix element between subbands LH1 and HH1 at k_i, respectively. The induced transition rate is related to the spontaneous rate by the Einstein relation, $W_{\mathrm{ind}}(k_i)=n(E)W_{\mathrm{spon}}(k_i)$, where $n(E)=1/[\exp(E/k_BT)-1]$ is the number of photons with energy E at temperature T.

A steady-state distribution can be obtained by setting Eq. (2) to be zero, then solved self-consistently with Eq. (1) using the Monte Carlo method. The result of quasi-Fermi levels for the structure with well and barrier widths of 70 and 50 Å, respectively, is shown in Fig. 1 for a hole density of $6\times10^{17}/\mathrm{cm}^3$, under a pumping current density of $J_p=90$ A/cm^2. The positions of quasi-Fermi levels relative to their respective subbands suggest that the population inversion

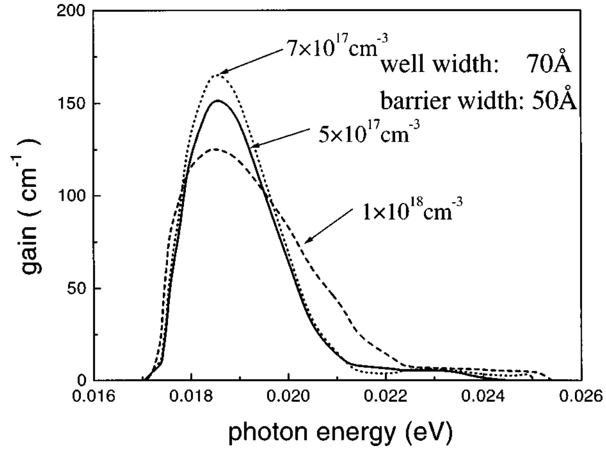

FIG. 3. Optical gain as a funciton of the photon energy for several hole concentrations in the QW structure of a GaAs well width of 70 Å and a AlGaAs barrier width of 50 Å.

can be established locally near the inverted-effective-mass region of subband LH1 even though the overall hole population in subband LH1 is less than that in subband HH1.

The expression for optical gain at a photon energy E can be given as

$$\gamma(E)=\frac{e^2\hbar\,\eta}{m_0^2E}|M_p|^2\int\frac{\Gamma}{[E-(E_l-E_h)]^2+\Gamma^2}\rho_r(E_l-E_h)\times[f_l(E_l)-f_h(E_h)]d(E_l-E_h), \quad (4)$$

where $n=1/\epsilon_0 c\tilde{n}=377\Omega/\tilde{n}$ is the impedance of the medium, $\rho_r(E_l-E_h)$ is the reduced density of states for the l-h transition, and Γ is the broading determined by all the dephasing processes including both intrasubband and intersubband scattering, but mostly by the much faster intrasubband process. Equation (4) is integrated over the range of E_l-E_h where the population inversion is established. If this region is wide enough compared to the broadening, the Lorentzian shape can then be approximated by $\pi\delta[E-(E_l-E_h)]$, and Eq. (4) reduces to

$$\gamma(E)=\frac{\pi e^2\hbar\,\eta}{m_0^2E}|M_p|^2\rho_r(E)[f_l(E_l)-f_h(E_h)]|_{E_l-E_h=E}. \quad (5)$$

In case that the broading is comparable to the energy range of population inversion, this approximation may lead to an overestimate of optical gain by about a factor of $\sqrt{2}$.

The optical gain in a laser structure with a well width of 70 Å and a barrier width of 50 Å as a function of photon energy is shown in Fig. 3 for several injected hole concentrations in the $5\times10^{17}\sim1\times10^{18}/\mathrm{cm}^3$ range. It should be pointed out that the optical gain is calculated under the conditions of liquid-nitrogen operating temperature and a relatively long tunneling time of 5 ns. A maximum optical gain of 170/cm at the laser wavelength of 67 μm can be achieved for the hole concentration of $7\times10^{17}/\mathrm{cm}^3$.

In summary, we have studied a novel valence intersubband laser based on the inverted-effective-mass feature in the light-hole subband in a GaAs/AlGaAs QWs. The advantage associated with this design is that the population inversion needs to be achieved only locally in **k** space within the inverted-effective-mass region, while the total population in the upper light-hole subband is only a small fraction of the population in the lower heavy-hole subband. We have theoretically investigated simple laser structures of quantum cascade scheme which consists of multiple isolated single QWs. Our results indicate that without establishing total population inversion between the two subbands LH1 and HH1, it is possible to achieve local population inversion in **k** space due to this inverted-effective-mass feature and obtain an optical gain in excess of 150/cm with a pumping current density about 100 A/cm^2 at the operating temperature of liquid nitrogen.

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