

Influence of disorder and a parallel magnetic field on a quantum cascade laser

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The luminescence spectra of a quantum cascade laser (QCL) in a strong magnetic field is influenced significantly by the presence of disorder (charged or neutral) in the system. An externally applied magnetic field parallel to the electron plane causes a redshift of the luminescence peak in the absence of any disorder potential. Our results indicate that the disorder potential tends to cancel that redshift and causes a rapid decrease of the luminescence peak. A similar behavior was observed in a recent experiment on a QCL in a parallel magnetic field by S. Blaser, L. Diehl, M. Beck, and J. Faist [Physica E 7, 33 (2000)]. © 2001 American Institute of Physics. [DOI: 10.1063/1.1343495]

Since the invention of the unipolar semiconductor quantum cascade laser (QCL) in 1994,^{1,2} there has been a series of innovations and improvements of performances in this field of intersubband light sources.³ The QCL has already established its potential as a tunable, high-power, and coherent source in the mid-IR spectral range and, therefore, amenable to a host of very useful applications.³ In the quest for further improvements of the QCL device, magnetic-field studies have recently been performed.⁴ However, no experimental or theoretical studies are available yet on the role of disorder in the optical properties of the QCL. Although the techniques of crystal growth have improved significantly in recent decades, interface roughness in QCL structures cannot be entirely eliminated. In a narrow quantum well, electrons are closer to the interface and are influenced by the irregularities or by the charged impurities confined at the interface. In this letter, we report on our findings that the effect of disorder is particularly significant on the luminescence spectra in the presence of a magnetic field. The QCL structure we have studied here is sketched in Fig. 1,⁵ where the parameters are taken from the QCL structure reported in Ref. 4.

The main results of the experimental work on the optical spectra of a QCL in a strong parallel magnetic field⁴ were a small blueshift of the emission peak, decrease of the emission intensity, and broadening of the peak in a strong magnetic field. It was also found that the single-particle theoretical model cannot explain these observations.⁴ This model predicts a redshift of the peak that cannot be canceled by the many-body corrections.⁵ In order to explain the experimentally observed tiny blueshift of the emission line, we consider the single-particle Hamiltonian

$$H = \frac{p_z^2}{2m(E)} + \frac{1}{2m(E)} \left(p_x + \frac{e}{c} Bz \right)^2 + \frac{p_y^2}{2m(E)} + V_{\text{conf}}(z) + V_{\text{dis}}(x, y), \quad (1)$$

where the magnetic field B is applied in the y direction, the vector potential is $\mathbf{A} = (Bz, 0, 0)$, $V_{\text{conf}}(z)$ is confinement po-

tential due to conduction-band discontinuity and bias electric field (Fig. 1), and $V_{\text{dis}}(x, y)$ is the disorder potential. The effective mass of the particle depends on the energy due to the band nonparabolicity. We consider the same disorder potential for both quantum wells in the active region (Fig. 1), i.e., electrons feel the same potential before and after emission.

We have studied the single-particle energy spectra and emission lines for two types of disorder potentials: for disorder due to the surface roughness in quantum wells and for disorder due to the doped charged impurities. The disorder potential in the first case is described by the potential $V_{\text{dis},1}(x, y)$, which has zero average and Gaussian correlations

$$\langle V_{\text{dis},1}(\mathbf{r}_1) V_{\text{dis},1}(\mathbf{r}_2) \rangle = V_0^2 e^{-(\mathbf{r}_1 - \mathbf{r}_2)^2 / l_0^2},$$

where $\mathbf{r}$ is the two-dimensional vector.

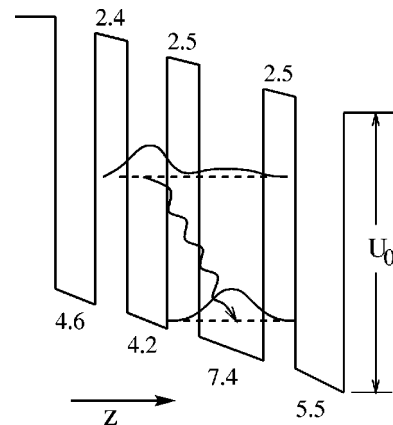


FIG. 1. Energy-band diagram (schematic) of the active region of a quantum cascade laser structure under an average applied electric field of 55 kV/cm. Only one period of the device is shown here. The relevant wave functions (moduli squared) as well as the transition corresponding to the laser action are also shown schematically. The numbers (in nm) are the well ($\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$) and barrier ($\text{Al}_{0.48}\text{In}_{0.52}\text{As}$) widths. Material parameters considered in this work are: electron effective mass m_e^* ($\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$) = $0.043 m_0$, m_e^* ($\text{Al}_{0.48}\text{In}_{0.52}\text{As}$) = $0.078 m_0$; the conduction-band discontinuity, $U_0 = 520$ meV, the nonparabolicity coefficient, $\gamma_w = 1.3 \times 10^{-18} \text{ m}^2$ for the well and $\gamma_b = 0.39 \times 10^{-18} \text{ m}^2$ for the barrier; and the sheet carrier density induced by doping, $n_s = 2.3 \times 10^{11} \text{ cm}^{-2}$. The energy difference between the two levels where the optical transition takes place is 132 meV.

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In the case of a charged impurity we assume that all impurities are in the same two-dimensional plane with position z_{imp} . The potential has the form

$$V_{\text{dis},2}(\mathbf{r}) = - \sum_i \frac{e^2}{\epsilon} \frac{e^{-|\mathbf{r}-\mathbf{R}_i|/d_{\text{sc}}}}{\sqrt{(\mathbf{r}-\mathbf{R}_i)^2 + (z-z_{\text{imp}})^2}},$$

where $\mathbf{R}_i$ is the two-dimensional vector describing the position of i th impurity, d_{sc} is the phenomenological constant which describes the screening of the impurity potential by electrons. In our present calculations we used $d_{\text{sc}} = 10$ nm. The two-dimensional density of impurities is equal to $n_{\text{imp}} = 2.3 \times 10^{11} \text{ cm}^{-2}$. The positions of impurities are uncorrelated.

To find the emission spectra of the system with the disorder potential $V_{\text{dis}}(x, y)$ we calculate from Hamiltonian (1), but without the disorder potential, the dispersion of the electron on the first and on the second subband (Fig. 1) for a given magnetic field B . Without any disorder the states are characterized by the two-dimensional momentum $(\hbar k_x, \hbar k_y)$. Taking these states as a basis we diagonalize the total Hamiltonian with the given disorder potential in a square geometry of size L with periodic boundary conditions. The emission spectra are then found from

$$I(\omega) = \left\langle \sum_{if} \delta(\omega - E_i + E_f) \left| \int \xi_2(z) \xi_1(z) dz \right|^2 \right. \\ \left. \times \left| \int \psi_i^*(k_x, k_y) \psi_f(k_x, k_y) dk_x dk_y \right|^2 \right\rangle, \quad (2)$$

where E_i, E_f are electron energies before and after emission; $\xi_1(z), \xi_2(z)$ are wave functions of the electron on the first and second subbands; and $\psi_i(k_x, k_y), \psi_f(k_x, k_y)$ are the initial and final wave functions for a given disorder potential. The summation in Eq. (2) is over all final states and over occupied initial states. The number of occupied initial states is determined by $N_i = L^2/n_{\text{el}}$, where $n_{\text{el}} = 2.3 \times 10^{11} \text{ cm}^{-2}$ is the electron density. The angular brackets correspond to averaging over the disorder potential.

To understand the properties of the emission line of our system with disorder, we consider the first terms of a perturbation theory in a magnetic field.⁶ In this case, Hamiltonian (1) for subband α can be rewritten as

$$H_\alpha = \frac{1}{2m(E)} \left(p_x + \frac{e}{c} B \langle z \rangle_\alpha \right)^2 + \frac{p_y^2}{2m(E)} + V_{\text{dis}}(x, y),$$

where $\langle z \rangle_\alpha = \int \xi_\alpha(z) z \xi_\alpha(z) dz$ and we disregard the small diamagnetic term. In this case, the energy spectra in the non-zero magnetic field is the same as for the zero magnetic field and the wave functions differ only by a phase factor, which corresponds to a translation in k space of the vector $(eB/\hbar c \langle z \rangle_\alpha, 0)$. The main effect is on the emission spectra because the intensity of the optical transition from the initial state i to the final state f is proportional to the overlap between $\psi_i(k_x, k_y)$ and $\psi_f(k_x - k_B, k_y)$, where ψ_i and ψ_f are the wave functions of the initial and final system, respectively, in the absence of a magnetic field

$$I_{if} = \left| \int \psi_i^*(k_x, k_y) \psi_f(k_x - k_B, k_y) dk_x dk_y \right|^2. \quad (3)$$

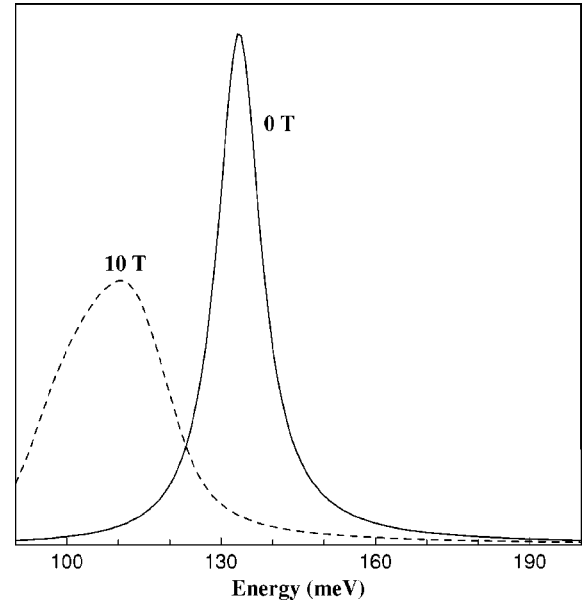


FIG. 2. Luminescence spectra of a quantum cascade structure in the presence of an externally applied parallel magnetic field, but in the absence of any impurity.

The wave vector k_B is equal to

$$k_B = \frac{e}{\hbar c} B (\langle z \rangle_i - \langle z \rangle_f),$$

where $\langle z \rangle_\alpha$ is the average position of electrons in subband α . For the system parameters considered here (Fig. 1), $(\langle z \rangle_1 - \langle z \rangle_2)$ is about 5 nm and $k_B \sim 0.1 \text{ nm}^{-1}$ at $B = 10$ T.

The position of the maximum of the emission line is determined mainly by the transitions from the ground state of the single-particle system. Without any disorder, the single-particle wave functions are plane waves $\psi_i(k_x, k_y) = \delta(k_x - k_{x,i}) \delta(k_y - k_{y,i})$, with the ground state at $\mathbf{k} = 0$. Clearly,

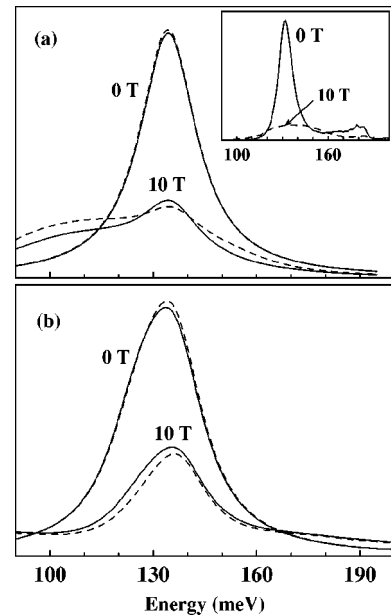


FIG. 3. Luminescence spectra of a quantum cascade structure in the case of (a) charge-neutral impurities and (b) charged impurities in the presence of an externally applied parallel magnetic field. The solid and dashed curves are explained in the text. The experimental results of Ref. 4 are shown as an inset.

the allowed transitions are then only from the ground state ($k_x=0$) of the upper subband to the excited states ($k_x=k_B$) of the lower subband, resulting in a redshift of the emission line in a magnetic field. A strong enough disorder will localize the lowest states. If the localization length is smaller than $1/k_B$, then the overlap between the initial ground state to the final ground state is large and the transition from a ground state to a ground state (different subbands) of the system is strong in a magnetic field and the redshift of the emission line is suppressed.

In Fig. 2, the emission spectra are shown for the system without disorder for two values of the magnetic fields. The large redshift, as expected, is clearly seen in Fig. 2. In Fig. 3, the emission spectra are shown for the system with disorder. In Fig. 3(a), where the disorder is charge neutral, the solid curves correspond to $V_0=30$ meV and $l_0=5$ nm, and the dashed curves correspond to $V_0=20$ meV and $l_0=5$ nm. In Fig. 3(b), the disorder is due to the charged impurity and the solid and dashed lines correspond to the separation between the impurity plane and the 4.2 nm quantum well (Fig. 1) at 3 and 4 nm, respectively. In both cases we see a large suppression of the redshift observed in Fig. 2. The emission line for the high-magnetic-field case is almost at the same energy as for the zero-field case, and in Fig. 3(b) there is a small blueshift of the peak. These results are qualitatively in agreement with the experimental data of Ref. 4 shown as an inset in Fig. 3. Further, in Fig. 3 the intensity of the luminescence peak

shows a rapid decrease in the presence of disorder and high fields because of the small overlap in Eq. (3).

The small blueshift in Fig. 3(b) is due to the band nonparabolicity. At zero magnetic field the nonparabolicity of the band structure allows the transitions from the ground state to the excited states. The magnetic field redistributes the transitions and increases the intensity of the transition into the ground state, which results in the small blueshift in Fig. 3(b). From our results it is clear that in a QCL device, magnetic-field-induced luminescence spectra⁵ can only be observed in the absence of strong disorder, i.e., devices with high electron mobility or for wider quantum wells.

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