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F. Y. Huang

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Quantum-confined field-effect wavelength tuning in a three-terminal double quantum well laser

F. Y. Huang
School of Electrical Engineering, University of Bath, Bath BA2 7AY, United Kingdom

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A three-terminal quantum-confined field-effect double quantum well laser device is proposed. The wavelength shift scheme caused by the field-induced change in the energy levels is demonstrated. With the current injected and the electric field applied to different wells, wide range wavelength shift can be achieved by changing the applied field.

Semiconductor laser diodes with tunable wavelengths have wide applications both in the interaction of laser beam with materials and in communications. A possible mechanism in quantum well (QW) laser with wavelength tunable by long-wavelength laser radiation has been proposed.[1] Recently, laser diodes with wavelength switched by the injection current between dual wavelengths have been realized experimentally both in the single QW and in the dual QW structure.[2,3] In this letter, we demonstrate the possibility of quantum-confined field-effect wavelength-tuning laser diodes (QC FEWT LDs) with wavelength tunable over a wide range by the applied electric field in a three-terminal double quantum well (DQW) structure.

The applied electric field can result in the following changes in the eigenstate of carriers in a quantum well structure: (i) shift of the electron and hole subband energies in the quantum well, (ii) change in the overlap of electron and hole wave functions in the quantum well, and (iii) tunneling of electron and hole out of the quantum well. Due to these effects, useful quantum well devices, such as multiquantum well electroabsorption modulators and field-effect light-emitter diodes (LEDs),[4,5] have been achieved. The changes in the absorption spectrum around the band edge due to the application of an electric field have been modeled by many authors and named the quantum-confined Stark effect (QCSE).[6,7] An interesting modulation principle based on the QCSE has been demonstrated by Wood *et al.*[4,8] The linewidths and photoluminescence energies have been studied in GaAs-AlGaAs multiquantum well modulators as a function of transverse electric field.[9] The field-dependent absorption spectrum has been calculated by computer modeling.[10]

Although the possibility of wavelength tuning by the applied electric field in a sequential multiquantum well laser using intersubband transition was studied a long time ago,[11] the wavelength-tuning mechanism in a single QW laser has only been mentioned in recent publications.[12] The difficulties of a quantum well laser with a high electric field applied across the active quantum well region can be attributed to the following two parts. First, a QW function laser will have a built-in field which is reduced as current is injected. When lasing occurs the field will be very small in case of forward biasing the heterojunction, so that it is difficult to apply high field in the quantum well with a usual heterojunction structure. Second, even though we can apply high field in the quantum well with special design of the structure, when lasing operates, the high density of injected carriers will screen the applied field dramatically, and hence, as a result the field-induced change in the laser emission will be reduced by the screening effect.

The first problem has been solved by using the three-terminal device. The current can be injected and the field applied in different directions along the QW, as suggested in Ref. 13. Another three-terminal device with the structure similar to that of a heterobipolar transistor for the LEDs has been demonstrated in experiment.[5] In this structure, carriers are injected from the emitter, while the electric field applied to the QW region can be controlled by changing the collector-base bias voltage. To reduce the screening effect due to the high injection carrier density in a quantum well laser, and hence, to obtain a wide range change of laser emission by the applied electric field, is the aim of this letter. A double quantum well device with three-terminal structure is suggested for this purpose. The current is injected into one of the quantum wells, while the high field is applied in another one. This structure enables us to apply high field and inject current simultaneously. Since the QW with applied field has no high carrier density, the screening effect can be neglected. And the lasing emission in the other QW can be controlled by changing the applied field in the QW through the strong coupling between the two wells. Hence, wide range wavelength shift or laser intensity modulation can be achieved.

In order to realize the device concepts, a possible structure is shown in Fig. 1(a). Two *n*-type AlAs cladding layers with higher barrier height to confine the optical field are used as the emitter and the collector. $Al_xGa_{1-x}As$ potential barriers are separated by two GaAs potential wells, with the *p*-type $Al_xGa_{1-x}As$ barrier as the base region connected to the *n*-type AlAs emitter. The energy-band diagram of the proposed structure is shown in Fig. 1(b) with an applied voltage across the collector and the base region. The difference of this structure from that of the field-effect single QW LEDs[5] is that, besides the double QW the bipolar transistor should be designed as *n-p-n* type. The current is injected from the emitter to the nearby quantum well 2, which is the active region when lasing occurs. The potential barrier between the two wells prevents the current flowing from well 2 to well 1, and hence the high field will not be screened by the injection carriers in well 1. The potential of well 2 is higher than that of well

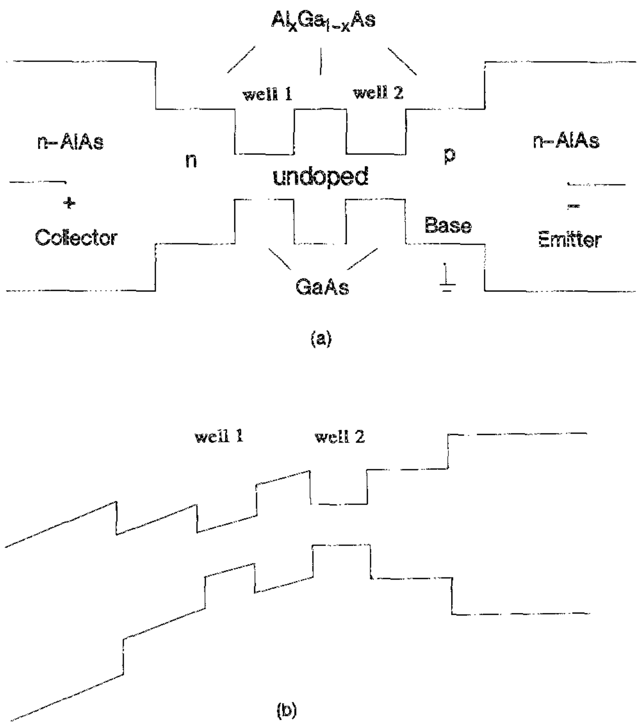

FIG. 1. (a) Schematic drawing of the energy-band diagram for the proposed three-terminal quantum-confined field-effect wavelength-tuning DQW laser. (b) The energy-band diagram when an electric field is applied across the collector and the base.

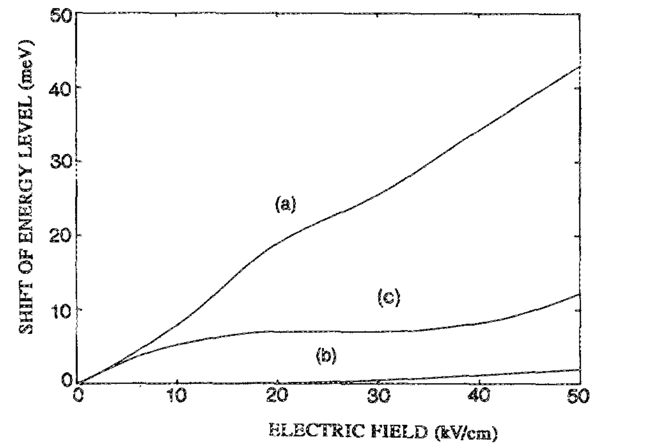

FIG. 2. Shifts of energy levels for electron (a) and heavy hole (b) in the DQW as a function of applied electric field. The well width is 75 Å and the barrier width is 50 Å. (c) Electron energy-level shift in a SQW of 75 Å well width. The screening effect is considered. The ground-state eigenenergies become smaller in all the cases due to the applied electric field.

1, so that the eigenstate in well 2 can be changed dramatically by charging the applied field in well 1.

In the presence of an electric field there is no true bound state for a finite quantum well potential depth. However, if the applied field is not excessively large, the state will have a long lifetime and can therefore be treated as quasibound. The tunneling resonance method,[7,14] with the transfer matrix relating the value of the envelope wave functions $\psi(x)$ and $1/m^*\partial\psi(x)/\partial x$ on either side of a potential step, is used to solve the Schrödinger equation of electrons and holes confined in a double quantum well in an electric field. This allows us to determine the electron and hole subband levels and the electron and hole tunneling rates as a function of the electric field. The field and the eigenstate in well 2 should be solved from the Poisson equation and the Schrödinger equation self-consistently. For an approximation, we assume that the field inside the well is totally screened by the carriers and hence the change of the energy band due to the electric field can be neglected. This is reasonable because of the higher carrier density for lasing to operate. Based on the numerical results shown in Ref. 13 for a single QW structure, the gradient of the potential within the QW is decreased, and the penetration of the electric field towards the inside of the QW is prevented dramatically by the surface-charged carriers. Under the above approximation, numerical calculations are carried out for a double quantum well of the band structure shown in Fig. 1(b) with the well width 75 Å separated by potential barrier of 50 Å width. The results are shown in Fig. 2 for the electron and heavy hole energy level shifts as a function of the applied field. For the model considered here both the electron and the heavy hole eigenstates become lower in energy when an electric field is applied. Parameters are chosen as follows. The Al concentration $x = 0.3$, the band offset ratio is 60:40 for the conduction and valence bands of GaAs and $Al_xGa_{1-x}As$, the concentration-dependent effective mass for electron is $m_c^* = (0.067 + 0.083x)m_0$ and hole $m_h^* = (0.48 + 0.31x)m_0$, respectively, with m_0 the electron mass. The band gap $E_g = 1.424$ (eV) and $\Delta E_g = 1.247x$ (eV). In this case, the electron potential well depth is 224.5 meV. The hole potential barrier height is 150 meV. In our calculations, the potential barrier outside the double quantum well is supposed to be much thicker than the QW width, and hence the effect of the AlAs cladding layers on the eigenstate can be neglected. For comparison the result of a single QW structure with the screening effect being taken into consideration is also shown. It is clearly seen that the energy level shift in the DQW is much larger than that in the SQW with the same well width. Since the energy level shift and the quasibound state lifetime are very sensitive to the width of the potential barrier between the two wells, for a practical laser device with larger wavelength tuning capability and also reasonable threshold current density, which requires larger energy level shifts and relatively longer lifetime of the quasibound state, it is necessary to choose an appropriate barrier width.

The lasing wavelength due to the recombination of electron and heavy hole can be estimated from

$$\lambda = \frac{1.2424}{(E_g + E_c + E_h)(\text{eV})}\,(\mu\text{m}).$$

TABLE I. Wavelength shifts in a three-terminal field-effect double quantum well laser are listed for different electric fields applied across the collector and the base region. The wavelength is red shifted relative to the original laser wavelength of 0.84 μm.

Field (kV/cm)	10	20	30	40	50
Wavelength shift (Å)	46	110	148	205	250

From the calculation above the wavelength shift for different electric field is shown in Table I for the 75 Å well and 50 Å barrier structure. Since the electron and the heavy hole ground-state eigenenergies become smaller in an electric field, the laser wavelength is red shifted. The wavelength shift is about 260 Å in a 50 kV/cm electric field with the original lasing wavelength of 0.84 μm.

As an applicable laser device, we also have to consider the increment of the threshold current density due to the application of an electric field. First, the electric field causes the decrease and broadening of the gain curve because of the reduction of the electron-hole overlap wave function and the carrier tunneling. For a given DQW laser diode with Γ, the confinement factor, and g_{th}, the gain necessary to overcome the total losses, the threshold gain is given by

$$g_{th}=\frac{1}{\Gamma}\left[\alpha_i+\frac{1}{\Gamma}\ln\left(\frac{1}{R}\right)\right],$$

where R is the reflectivity of the end mirrors and α_i is the total internal losses. Since the application of the field, the optical absorption in the quantum well coupling to the active region will be raised considerably, and hence the threshold gain will be increased. The threshold carrier density N_{th} for lasing to occur can be obtained from the gain and carrier density relation by imposing the threshold gain. The decrease of the gain curve and the increase of the threshold gain result in the increase of the threshold carrier density. The laser threshold current density can be obtained from the laser rate equation and is given by

$$J_{th}=e\,WN_{th}/\tau_s,$$

where the carrier lifetime includes τ_1, the tunneling lifetime, and τ_0, the nonradiative lifetime, with $1/\tau_s=1/\tau_1+1/\tau_0$. It can be seen that as the applied field becomes larger the tunneling of carriers becomes important and the tunneling lifetime becomes dominating, which causes increment of the threshold current. If the threshold carrier density in a SQW LDs in the absence of any electric field is N_{th}^0, and the corresponding threshold current density is J_{th}^0, then the threshold J_{th} of the DQW LDs in an applied field is given by

$$J_{th}=\frac{N_{th}}{N_{th}^0}\left(1+\frac{\tau_0}{\tau_1}\right)J_{th}^0.$$

In the case of quantum well laser considered here with an electric field 50 kV/cm, the quasibound state lifetime is about the same order as the carrier nonradiative lifetime τ_0, and we estimate from the overlap of electron-hole wave function that the threshold carrier density is increased about several times larger than the original value, which causes the threshold current density about an order of magnitude higher than that of the same quantum well laser without the electric field. Because of the low threshold current density of the quantum well laser realized in experiment, it is reasonable to hope that the relatively higher threshold current can be achieved for the double quantum well laser in a moderate electric field.

In summary, we have proposed a three-terminal quantum-confined field-effect double quantum well laser device to obtain wide range wavelength-tuning capability caused by the field-induced change in the energy levels of electron and hole. The key point is to inject the current and apply the high field in different wells, and hence the screening effect due to the high carrier concentration can be reduced. The DQW structure is used to release the confinement of the injected carriers by the potential barrier, so that the eigenstate can be changed largely through the strong coupling between the two quantum wells by the applied electric field. The laser wavelength can be tunable at the cost of higher threshold injection current density because of the increase of the optical absorption, reduction of the gain curve, and the carrier leakage.

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