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Population inversion in an optically-pumped single quantum well

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Abstract - An optically-pumped intersubband laser generator is proposed in which the continuum states above an $Al_{0.2}Ga_{0.8}As$ - GaAs - $Al_{0.2}Ga_{0.8}As$ single quantum well with a width of L = 17 nm serve as the highest level in a four-level laser system. The design allows much greater flexibility in the choice of pumping source and simplifies considerably the device fabrication. We have obtained the electronic subband structure of the proposed device and utilized a simple rate equation approach to examine the electron density in different states under optical pumping.

A. Introduction

Although the present investigation into intersubband laser emission in low-dimensional semiconductor systems (LDSSs), is dominated by the quantum cascade laser (QCL) realized from semiconductor superlattices [1], optically pumped intersubband lasers (OPISLs) based on polar-semiconductor quantum well structures have been proposed and studied since 1995 by several groups [2-5]. From a fundamental point of view, the study of OPISLs provides an opportunity to examine the excitation and relaxation of electrons in a LDSS via intersubband transition events caused by electron interactions with photons and phonons. Moreover, it has been realized that GaAs-based QCLs cannot produce long-wavelength laser radiation because of the problems with thermal management, where the laser emission is suppressed when the radiation frequency approaches that of the optical phonons. In contrast, OPISLs [2-5] are designed to take advantage of the electron-phonon interactions and can therefore achieve longer wavelength laser emission. A practical three-level OPISL was proposed [3] in 1995 using an AlGaAs-GaAs double quantum well structure and a CO_2 laser as the pumping source. Since then some alternative designs such as employing AlGaAs-GaAs step quantum wells which behave as three- [4] or four-level [5] OPISLs under CO_2 laser pumping, have also been proposed. However these devices suffer two major drawbacks: (i) they are not very easy to fabricate due to their relatively complicated structures; (ii) there is little flexibility in the choice of pumping source, since the energy of the pumping radiation must correspond to the separation between subbands.

B. Proposed device

We propose a new OPISL device which consists of an $Al_{0.2}Ga_{0.8}As$ - GaAs - $Al_{0.2}Ga_{0.8}As$ *single* quantum well with a GaAs layer thickness of L = 17 nm. We consider a typical modulation-doped structure with a donor (Si) concentration $N_d = 2 \times 10^{18}$ cm^{-3} in the AlGaAs layers, a spacer thickness s = 5 nm measured from the AlGaAs/GaAs interfaces, and a background acceptor concentration $N_a = 2 \times 10^{16}$ cm^{-3} in the GaAs layer. The device parameters have been chosen such that for the three subbands present, $\varepsilon_1 - \varepsilon_0 = 37.1$ meV

(close to the optical phonon energy $\hbar\omega_{LO} \approx 36.6$ meV), $\varepsilon_2 - \varepsilon_1 = 57.6$ meV (much larger than $\hbar\omega_{LO}$), while the energy separation between the top of the well U_0 and subband 2 is $U_0 - \varepsilon_2 = 36.0$ meV again close to $\hbar\omega_{LO}$. With the application of a pumping field of frequency $\hbar\omega > U_0 - \varepsilon_0 = 129.7$ meV (or wavelength $\lambda < 9.2$ μm), electrons in the lowest subband are pumped into continuum states above the well. Relaxation of electrons from continuum states into subband 2 and from subband 1 into subband 0 via electron-LO-phonon emission will be relatively rapid due to the electro-phonon resonance effect (EPR) [6]. However, since $\varepsilon_2 - \varepsilon_1$ and $\varepsilon_2 - \varepsilon_0$ are much larger than $\hbar\omega_{LO}$, electrons in subband 2 cannot be scattered quickly into the lower subbands via nonradiative electronic transition channels. The principal advantages of the present laser device are: (i) The device looks simpler, is much easier to fabricate and, as a result, should be produced more cheaply. (ii) The design allows much greater flexibility in the choice of pumping source. (iii) Due to the simple sample structure, we can easily produce a multiple quantum well system based on this single quantum well laser to enhance optical gain, laser efficiency, laser output power etc.

C. Theoretical results

To examine theoretically the conditions under which the electron populations in subbands 2 and 1 can be inverted, we use the steady state Boltzmann equation to derive the rate equations for the device. We consider a system in which bound-to-bound (2D $\leftrightarrow$ 2D) and

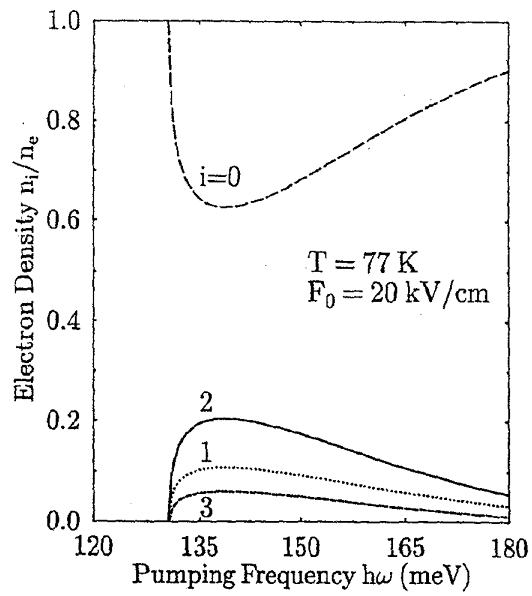

Fig. 1: Electron density in different levels n_i versus frequency of the pumping field at a fixed pumping intensity F_0 and a fixed temperature.

bound-to-continuum (2D ↔ 3D) transitions are present. We include interactions between electrons and LO-phonons and between electrons and an optical pumping field which is linearly polarized along the growth direction of the quantum well. A Maxwellian distribution function is used to describe the statistical distribution of the electrons.

The areal electron density n_i in different levels is shown in Fig. 1 as a function of pumping frequency at a fixed field strength $F_0 = 20$ kV/cm and temperature T = 77K. Here, $i < 3$ and $i = 3$ represent respectively the bound and the continuum levels and n_e is the total electron density. We see that when the condition $\hbar\omega + \varepsilon_0 - U_0 > 0$ is satisfied, electrons in the bound levels can be pumped into the continuum states and the electron populations in subbands 2 and 1 can be inverted via electron–LO-phonon scattering. In sharp contrast to the strict selection rules for optical pumping of electrons between bound levels in a two-dimensional electron gas (2DEG) system, bound-to-continuum pumping can be effective over a wide range of frequencies [7]. The theoretical results indicate that the optical pumping efficiency, ie. the rate to pump electrons from a bound level with energy ε_n to continuum states, is proportional to $I_0 / (\hbar\omega + \varepsilon_n - U_0)^{1/2}$, where I_0 and ω are respectively the intensity and frequency of the pumping field. Therefore, we can use any far infra-red (FIR) source (not necessarily a FIR laser) as the pumping field to operate the device as long as $\hbar\omega > U_0 - \varepsilon_0 = 129.7$ meV is satisfied. We find that the optimum pumping frequency is $\hbar\omega \approx 139$ meV corresponding to a wavelength $\lambda \approx 8.9$ μm.

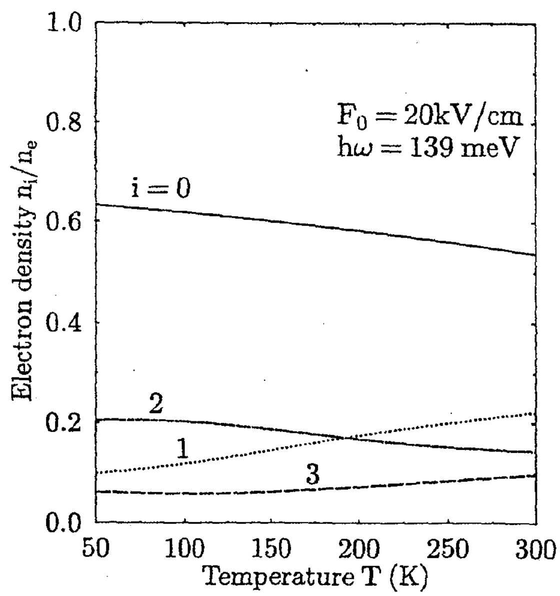

Fig. 2: Dependence of the electron density n_i in different levels on temperature at a fixed pumping field with frequency ω and electric field strength F_0.

The dependence of the electron density n_i on temperature is shown in Fig. 2 at a fixed pumping field. Here we see that the population inversion between subbands 2 and 1 can only be achieved when $T < 195K$ at $\hbar\omega = 139meV$ and $F_0 = 20$ kV/cm. At higher temperatures population inversion cannot be maintained due to the increased probability of LO-phonon absorption induced transitions from subbands 0 to 1 and from subband 3 to the continuum. With increasing intensity of the pumping field, the regime within which the population inversion can be observed is extended to higher temperatures. Our calculations show that a pumping field of at least 35 kV/cm is required for room temperature operation.

D. Conclusion

In this paper, we have proposed a new OPISL device, based on a simple single quantum well structure, which has been designed to allow increased flexibility in the choice of pumping sources. The results obtained from calculations show that a FIR source with $\hbar\omega > 130$ meV (or wavelength $\lambda < 9.2$ μm) and $F_0 \approx 10$ kV/cm would be sufficient to operate the device as an intersubband laser with a frequency $\hbar\omega \approx 57.6$ meV (or $\lambda \approx 21.5$ μm). This wavelength is much longer than those generated by GaAs-based QCLs which are typically [8] limited to $\lambda < 5$ μm. For a field strength of $F_0 = 20$ kV/cm, we find that population inversion can be maintained for temperatures up to T = 195 K. In order to operate the device at room temperature, however, a pumping field of intensity $F_0 \geq 35$ kV/cm is required. It is our hope that the simple OPISL device proposed in this article can be realized and tested experimentally.

Acknowledgments

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