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# A 35–177 $\mu$m tunable intersubband emitter for the far-infrared

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**Abstract.** Under the influence of a perpendicular electric field the mini-bands of a superlattice break up and form localised electron states within each quantum well. The energy separation between adjacent well states is proportional to the field and the system has become known as a 'Stark Ladder'. This work investigates the potential of superlattices within the Stark Ladder regime as tunable intersubband emitters for the far-infrared region of the spectrum.

## 1 Introduction

The recent rapid development of unipolar semiconductor (or quantum cascade) lasers, based on intersubband transitions in quantum well structures, has been impressive, with recent reports of high power devices operating at room temperature [1]. The majority of this work has centred around emission in the mid-infrared (4–12 $\mu$m) region of the spectrum, and more recently attention has turned towards field tunable devices [2] which promise much in the way of application.

Another area of increased interest and potential exploitation of unipolar semiconductor emitters/lasers is the far-infrared (300–30 $\mu$m) or terahertz ($1\text{–}10\times10^{12}$ Hz) region of the spectrum [3]. Indeed tunable terahertz emission has been demonstrated [4]. This theoretical work explores a new design for a far-infared emitter based on intersubband transitions between the conduction band states of adjacent wells of a Stark Ladder. The main benefit of this two-level system is the extent of its tuning range, with the particular design advanced here having a subband separation tunable by an electric field from 5 to 37 meV. This tunability offers the potential for light emission from 33 to 248 $\mu$m.

## 2 Theoretical methods

The envelope function/effective mass approximations were assumed, hence the one-dimensional Schrödinger equation can be written as

$$\left(-\frac{\hbar^2}{2}\frac{\partial}{\partial z}\frac{1}{m}\frac{\partial}{\partial z}+V(z)-eF(z-z_0)\right)\psi=E_n\psi \tag{1}$$

where $V(z)$ represents the conduction band profile and $F$ is the electric field strength, note the origin $z_0$ of the field has been chosen as the centre of the quantum well structure. This was solved with a numerical shooting technique.

After some optimization, the basic design settled upon was a superlattice of 50 Å $Ga_{0.8}Al_{0.2}As$ barriers and 50 Å GaAs wells, hence the period $L$ = 100 Å. One of the

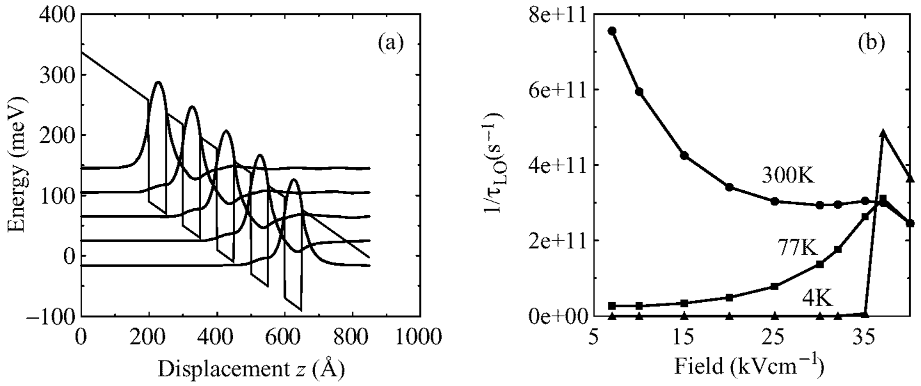

**Fig 1.** (a) Schematic representation of wave functions, energy levels and confining potentials in the Stark Ladder regime, (b) Electron-LO phonon scattering rates from well $m$ to $m+1$ as a function of electric field.

criteria being low field miniband breakup in order that the subband separations quickly satisfied the Stark Ladder demand

$$E_{n+1} - E_n = eFL \tag{2}$$

i.e. an emission frequency proportional to the field. An additional criteria being a reasonable overlap of the wave functions centred in adjacent wells to ensure relatively short spontaneous emission lifetimes. The basic design operation is similar to quantum cascade lasers—electrons scatter down the 'ladder' of localised states. As shown below the majority of energy transitions are non-radiative, but some produce the desired photons. The equal spacing of the energy levels leads to monochromatic emission, the frequency of which is proportional to the applied electric field.

It was shown that a 5 well structure was of sufficient extent to exhibit the energy level structure of the infinite superlattice, hence this system was adopted in these theoretical calculations. Fig. 1(a) illustrates the Stark Ladder regime of the superlattice. At this point the electric field is of sufficient magnitude to localize the electron wave functions to 1 or 2 wells. Calculations showed that indeed the Stark Ladder criteria of Eq. 2 was applicable for fields of 5 kVcm$^{-1}$ and upwards, hence the desired emission properties of tunability and linewidth are fulfilled. The feasibility now centres around the expected power output of the device.

With this aim, the electron-electron [5] and electron-phonon (using bulk acoustic and longitudinal optic (LO) modes [6]) scattering rates were calculated, assuming independently thermalized subbands each of carrier density $10^{10}$ cm$^{-2}$. The radiative transition rate was calculated using the approach of Smet [7]. The results confirmed that scattering rates from level $|n+1\rangle \rightarrow |n\rangle$ were equal for $n = 2$, 3 and 4: it can be seen from Fig. 1(a) that the lowest energy state $|1\rangle$ does experience an 'end' effect. Thus the rates are applicable to a hypothetical infinite structure and are discussed below.

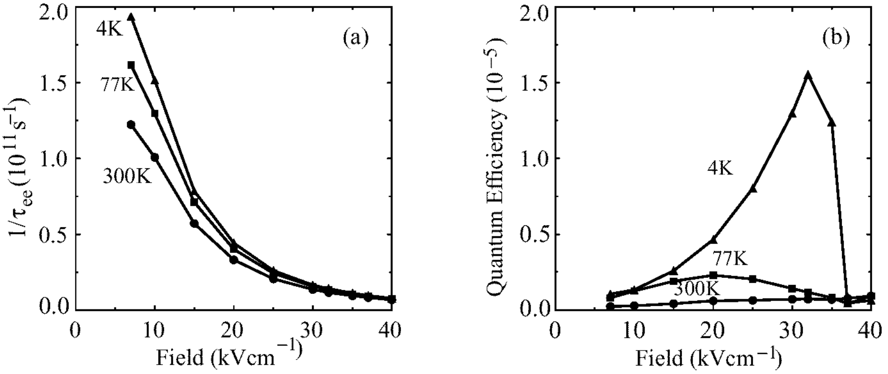

**Fig 2.** (a) Electron-electron scattering rates from well $n$ to $n + 1$ as a function of electric field, (b) internal quantum efficiency.

## 3 Results and discussion

As mentioned above, there are three scattering mechanisms which, *a priori*, are expected to be relevant. However the calculations show that electron-acoustic phonon scattering is weak in this system, of the order of perhaps 5% of the electron-LO phonon rate, and can therefore be ignored. The important mechanisms of electron-LO phonon and electron-electron scattering are displayed in Figs. 1(b) and 2(a). It can be seen that typically the electron-LO phonon scattering rate is a factor of 4 larger than the electron-electron rate.

With $L$ in Å and $F$ in kVcm$^{-1}$ then the subband separation is simply given by $E_{n+1} - E_n = F$ meV which allows for easy interpretation of the electric field into an emission energy. The LO phonon energy in GaAs is 36 meV, hence the rapid 'switch on' of this scattering mechanism as the subband separation reaches this value (at $F$=36 kVcm$^{-1}$), is illustrated by the data at 4 K. The higher temperature curves of Fig. 1(b) are in contrast to this and display scattering even though the subband separation is below the LO phonon energy. This is due to emission from the high energy thermal tail of the upper subband Fermi-Dirac distribution. Whilst this thermal effect is important, an explanation of the exact field dependencies of the scattering rates requires an appreciation of the fact that the overlap of the initial and final wave functions decreases with an increasing field and the increasing subband separation leads to a increasing change in momentum between the states, both factors lead to a reduction in rate.

In contrast the temperature dependency of the electron-electron scattering rate is much weaker and derives from the thermal broadening of the distributions and the thermal dependency of the screening factor. Again the scattering rates decrease due to an increasing subband separation which requires a larger change in carrier momentum.

The effect of both these non-radiative transitions on the internal quantum efficiency, defined as the ratio of the radiative to the total non-radiative scattering rate, is displayed in Fig. 2(b). As might be expected the quantum efficiency is highest at low temperatures, due mainly to the suppression of LO phonon emission. Most importantly, at 4 K it peaks at subband separations just below the LO phonon energy at 34 meV=37 $\mu$m.

The quantum efficiency at this point is $\sim 2 \times 10^{-5}$. Although this appears quite low it needs to be considered in context. For every $N$ electrons in well $m$ say, only $\frac{1}{50,000}^{\text{th}}$ emit a photon in the process of scattering to well $m+1$. However if there are a 100 repeats in the superlattice then the number of photons emitted is $\frac{1}{500}^{\text{th}}$ of the number of electrons passing through the system. Fig. 2(b) shows that the expected performance is better at short wavelengths, down to the minimum of 35 $\mu$m (= 35 kVcm$^{-1}$). At longer wavelengths the expected number of photons generated decreases, the maximum wavelength is at $F = 7$ kVcm$^{-1}$ $= 177\,\mu$m by which the quantum efficiency has fallen by a factor of 10 from its peak value.

The peak in quantum efficiency at 77 K is a factor of 8 less than that at 4 K and occurs for a subband separation of 20 meV = 62 $\mu$m. Further increases in temperature give rise to further decreases in efficiency.

## 4 Conclusion

Intersubband transitions between the equal spaced steps of a Stark Ladder offer potential for tunable far-infrared emission. The particular design advanced here, to illustrate the principle, offers potential for emission tunable from 35 to 177 $\mu$m with a peak in efficiency at the shorter wavelengths.

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