Quantum well intersubband transitions as a source of terahertz radiation

P. Harrison, R. W. Kelsall, P. Kinsler, and K. Donovan

Abstract—**It is shown that unipolar quantum well systems have potential as sources of terahertz radiation. It is demonstrated that the electronic interactions within these systems must be manipulated in order to favour radiative emission rather than non-radiative loss. Designs are advanced for tunable emitters and optically excited terahertz lasers.**

Keywords— **Terahertz, far-infrared, intersubband, quantum cascade lasers**

I. Introduction and theory

THE conventional approach to terahertz frequency generation is based on oscillating currents in non-linear electronic devices. In contrast, optical techniques rely on photon emission via electron (or hole) transitions between discrete energy levels. Terahertz photons of frequency 1-10 THz can be produced with energy level separations of between 4 and 41 meV—an energy range which is readily accessible using the confined states in quantum well structures.

A. Quantum wells and subbands

The confined levels within either the conduction or valence band of a semiconductor heterostructure have one less degree of freedom than bulk, thus giving them a two-dimensional character. Whilst the carriers are confined along one direction (z-) they are free to move in the other two spatial co-ordinates (x- and y-), hence the confined levels are broadened into 'subbands'—as opposed to the three-dimensional energy 'bands' of bulk semiconductors. For an introduction to semiconductor heterostructures, see for example, [1].

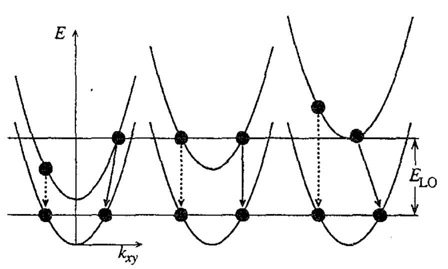

Fig. 1. Energy versus wavevector (momenyum) diagrams for radiative (dashed, vertical) and non-radiative (solid, vertical or diagonal) intersubband transitions for energy separations below (left), equal (centre), and above (right) the LO phonon energy

The energy separation of subbands can be easily engineered, by altering layer thicknesses within the heterostructure, to obtain photon frequencies covering the majority of the infrared spectrum. Helm[2] first observed radiative emission in the mid-infrared and so spurred an enormous interest in 'intersubband transitions'. Progress in this field has been rapid, with the development of the first intersubband laser in 1994[3] and now even room temperature devices[4]. Note these devices are 'unipolar' in that they are only doped with one type of impurity (usually n-type), as opposed to traditional 'interband' bipolar laser diodes which have both n- and p-type doping.

The extension of these developments to the far-infared or terahertz region of the spectrum is non-trivial, in that the much reduced subband separations become of the order of dominant phonons (longitudinal optic (LO) in III-V materials). This causes an increase in the competing non-radiative scattering rates, which *can* be detrimental to radiative emission. This paper reviews the recent progress in the understanding of these scattering processes and proposes designs for both terahertz lasers and tunable emitters.

B. Transitions between subbands

Exploiting transitions between subbands (otherwise known as *'intersubband transitions'*) in order to generate radiation requires an understanding of the various competing processes. For example, populating an excited state with a number of electrons (or holes) is sufficient to induce transitions to a lower energy state, as a system will always try to minimise its energy. However only a fraction of those transitions will be radiative, with energy emitted as photons; the majority involve scattering with the lattice, resulting in non-radiative energy, i.e., phonon emission. The strength of a transition is represented by its *'scattering rate'*, which is the number of transitions per unit time, or the reciprocal of the lifetime of an electron (or hole) in an energy level, i.e., $1/\tau$.

II. Intersubband scattering at terahertz subband separations

As illustrated in Fig. 1, the subbands due to the in-plane motion of the electrons are parallel and (at low momenta) parabolic, hence a variety of possibilities exist for phonon and photon emission at subband separations of terahertz energies. These are illustrated schematically in Fig. 1. As photons have very little momentum their emission causes a negligible change in the electron momentum and hence the radiative transitions on Fig. 1 (marked by dashed lines) are vertical. The photon does however have a finite energy

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$h\nu$ equal to the subband separation $E_2 - E_1 = \Delta E_{21}$. If the subband energy separation is equal to the LO phonon energy (other phonon modes do exist, but in this work concentration will be focused on the dominant mode), then the electron can emit a phonon and satisfy the conservation of energy also with a vertical transition, as in the centre diagram. This represents the generation of a low momentum phonon and is the fastest of the three scenarios. On the other hand if the subband separation is less than (left hand diagram) or greater than (right hand diagram) the LO phonon energy then the resulting transition has to be accompanied by a momentum change. This is indicated by the diagonal (solid) lines in Fig. 1; such transitions occur slower than the former case.

A. Electron-phonon scattering

For illustrative purposes an infinitely deep single GaAs quantum well is employed, thus exhibiting completely confined wave functions. Such a system is useful as the subband separation ΔE_{21} can be varied, by adjusting the quantum well width, without altering the electron wave functions, on which all scattering rates depend. Fig. 2 displays the results of calculations of the electron-LO phonon scattering rate as a function of the subband separation, the computational methods employed have been outlined in earlier works[5].

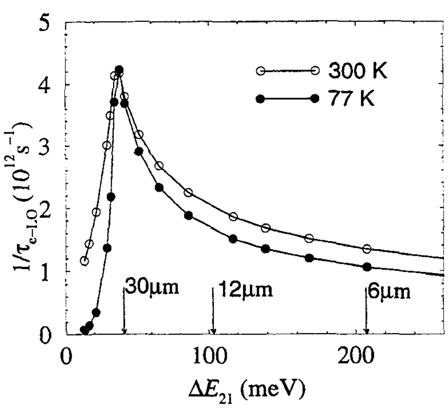

Fig. 2. Electron-LO phonon scattering rate versus energy separation between the lowest two subbands of an infinitely deep GaAs quantum well

The two main features of Fig. 2 are: (i) the scattering rate increases as the subband separation decreases through the mid-infrared (6-12 μm) before peaking as ΔE_{21} equals the LO phonon energy, near the onset of the far-infrared (30 μm); (ii) below the LO phonon energy the scattering rate is very sensitive to temperature. In terms of competing with an accompanying radiative transition, the former point is a detrimental effect when moving to longer wavelengths; however beyond 30 μm (below the LO phonon energy) this non-radiative mechanism is suppressed, particularly at low temperature.

Fig. 3 displays the origins of this suppression and the temperature sensitivity. At low temperatures the electrons, described by Fermi-Dirac statistics, occupy all the lowest energy levels. Although an electron in the upper subband near the top of the energy distribution, may have sufficient energy to emit a phonon, the states to which it would scatter are all occupied and hence the transition is prohibited (Pauli exclusion). At higher temperature however, the electrons occupy a broader range of energy states yielding, higher energy electrons in the upper subband *and* empty states in the lower subband; thus LO phonon emission is possible.

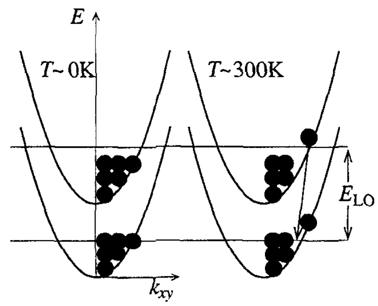

Fig. 3. Prevention of LO phonon emission at low temperatures due to Pauli exclusion, for subband separations less than the LO phonon energy (left), and the activation of such processes due to the thermal broadening of the electron energy distribution at elevated temperatures

B. Electron-electron scattering

Electron-phonon scattering is *'inelastic'* in that the total energy of the electrons is reduced by such an event. Another non-radiative mechanism is electron-electron scattering which is *'elastic'* in that the total electron energy remains constant.

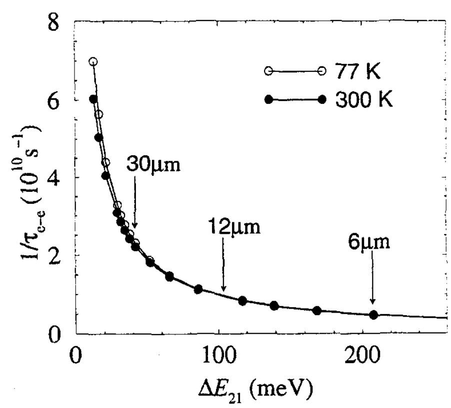

Fig. 4. Electron-electron scattering rate versus energy separation between the lowest two subbands of an infinitely deep GaAs quantum well

Fig. 4 displays the results of calculations of the intersubband electron-electron scattering rate, again as a function of the subband separation ΔE_{21}; explanation of the computational methods employed is available in an earlier

work[6]. Again it can be seen that this non-radiative rate increases as the energy separation between the subbands is reduced from the mid-infrared to the far-infrared range.

C. Electron-photon scattering

Finally the remaining scattering rate that is of importance is the electron-photon or radiative scattering rate itself. The two-dimensional form of Smet *et al.*[7] implies that the radiative scattering rate $\frac{1}{\tau_{\text{rad}}} \propto \Delta E_{21}$, i.e., the emission of photons becomes less likely, as the subband separation decreases—a detrimental effect.

D. Summarising

Thus, in summary, the successful design of far-infrared/THz lasers is made difficult by the complex behaviour of the electron scattering rates. In particular, the electron-LO phonon scattering rate has a peak at 30 μm, an d ahigh temperature sensitivity for longer wavelengths. In addition the increase in the non-radiative competing mechanism of electron-electron scattering as well as the decrease in the radiative rate both suggest a reduction in the quantum efficiency of terahertz devices compared to those of the mid-infrared. Despite this, progress has been made in the design of quantum well systems to improve quantum efficiencies, and indeed emission in the terahertz region via intersubband transitions has recently been observed[8].

III. Engineering the scattering rates to favour terahertz emission

A. Electrically injected emitters

'Electrically injected' or *'electroluminescent'* emitters are devices whose energy input arises from injected electrons (an electric current). A terahertz emitter requires a semiconductor heterostructure in which energy level separations can be produced which are in the range 4-41 meV (1-10 THz).

When an electric field is applied to certain superlattices, the energy states (initially extended over the whole structure) localise. At high enough fields the state can be localised across just one or two wells and from this point onwards its energy is proportional to the field F. Such a system is known as a Stark Ladder as the energy levels, at any field, are equally spaced. A five well system thus produces 5 states, with the energy separation between the states being proportional to the field. A superlattice in this state offers an ideal opportunity to create a *tunable* terahertz emitter, in that the emission energy $\Delta E = E_{n+1} - E_n = eFL$ is of the order of a few tens of meV *and* is proportional to the field.

The operation of the device is illustrated schematically by Fig. 5. Electrons are injected through an electrical contact from the right at high potential, they then scatter down through the series of discrete energy levels. At each level they can undergo either a non-radiative (electron-LO phonon or electron-electron) or radiative transition. The relative strengths of each are often summarised in terms of the *'internal quantum efficiency'* which is equal to the

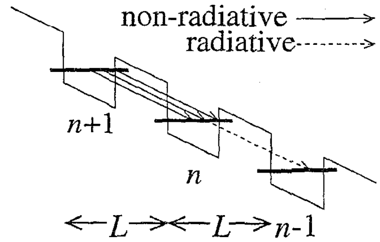

Fig. 5. Electron-phonon (non-radiative) scattering competes with photon emission (radiative scattering) as the electrons 'cascade' through the energy level 'staircase'

fraction of transitions which are radiative. Generally in this type of device this is quite low, peaking at around 2×10^{-5}, at a field of 34 kVcm^{-1} and at a temperature of 4 K[9]—at which the electron-LO phonon non-radiative scattering is severely suppressed. Such an efficiency means that for every 50,000 electrons in level $n+1$ only 1 emits a photon when scattering down to level n. However if the superlattice is fabricated with say 100 periods (quantum wells) then the number of photons generated by 50,000 electrons passing through the complete system is 100$\times$ as large, giving an internal quantum efficiency of 2×10^{-3}, which although still low, is more promising.

If the superlattice is doped to provide an electron density per unit area of N in each well at equilibrium operating conditions, then the current density through the device is given by $J = Ne/\tau$, where τ is the carrier lifetime in any of the levels, i.e., $\frac{1}{\tau} = \frac{1}{\tau_{\text{e-e}}} + \frac{1}{\tau_{\text{e-LO}}} + \frac{1}{\tau_{\text{rad}}}$. Correspondingly the number of photons generated per well equals N/τ_{rad}. With this approach Donovan *et al.*[9] found that a dopant density producing 10^{11}cm^{-2} in each well produced a current density of 2.2 kAcm^{-1} at an electric field of 34 kVcm−1, in turn this device would produce 2.1×10^{19} photons per unit area per unit time per well. For a mesa structure of area 1 cm^{-2} emitting photons of energy 34 meV, then this implies a peak output power of about 1 mW at a wavelength of 36 μm or 8 THz.

Transitions of this nature have recently been observed[10].

B. Optically excited systems

If motivated by the desire for lasing from a solid state source, the next stage in the development from an electroluminescent emitter would be an *'optically excited'* system. This offers the potential of simplifying the design of a lasing structure by removing the necessity to inject electrons though a contact and maintaining a current flow.

Lasing relies upon stimulated emission occuring within an optical cavity, which in turn produces the amplification. In this work attention will be focussed on producing stimulated emission within the active region. A necessary condition for stimulated emission is a population inversion between two energy levels, which in the case of an intersubband system would imply that their must be more electrons in the upper subband than in the lower. To sustain

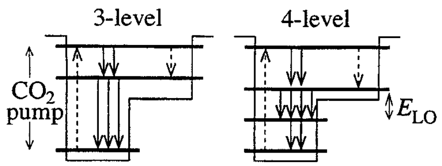

Fig. 6. Three- and four-level optically excited systems based on asymmetric quantum wells

a population inversion at least one other level is required.

Consider first a 3-level system: the rate of change of the population of the second level is given approximately by the rate equation

$$\frac{dn_2}{dt} = \frac{n_3}{\tau_{32}} - \frac{n_2}{\tau_{21}} \quad (1)$$

When the system is at equilibrium, the population of the second level remains constant, hence $\frac{dn_2}{dt}$=0. Given this then if $\tau_{32} > \tau_{21}$ i.e., if the lifetime in the lower state was *less* than the lifetime of the upper state, then $n_3 > n_2$— a population inversion would exist between the third and second levels, thus fulfilling the criteria for stimulated emission.

Berger[11] proposed a 3-subband asymmetric quantum well as a potential design for a terahertz laser, with a populaiton inversion between the third and second subbands. Fig. 6 illustrates the mode of operation. The system is excited by the 10.6 μm line of a CO_2 laser which excites the reservoir of carriers in the lowest subband to the third subband. Varying the structural parameters of the quantum well allows the excitation criteria to be fulfilled, while at the same time tuning the emission energy $E_3 - E_2$ across the terahertz region of the spectrum.

Using the methods outlined above, earlier work[5], [6] entailed a study of the scattering rates between the subbands in asymmetric quantum wells. The population ratio τ_{32}/τ_{21} is plotted in Fig. 7 (filled symbols). The main conclusions are: that the population ratios peak around 5-7 THz; they are greater at lower temperatures, and are always less than 1 at 300K. The final point implies that stimulated emission would not be observed at elevated temperatures.

Considering again the criteria for population inversion, $\tau_{32} > \tau_{21}$: then if the lifetime of the lower laser level could be reduced, then the population ratio would be improved. The right hand structure of Fig. 6 is an attempt at such a lifetime reduction. An additional fourth subband is introduced beneath the lower laser subband to enhance the scattering out (reduce the lifetime), lasing is now designed to be between the fourth and third subbands. The structural parameters of the asymmetric quantum wells were varied[5] in order to retain the same optical pump energy, but to hold the new subband exactly an LO phonon energy below the lower laser subband, thus maximising the lifetime reduction effect.

Fig. 7 also displays the population ratios for these 4-subband systems (open symbols)[12]. It is apparent that the population ratios are much improved for the higher

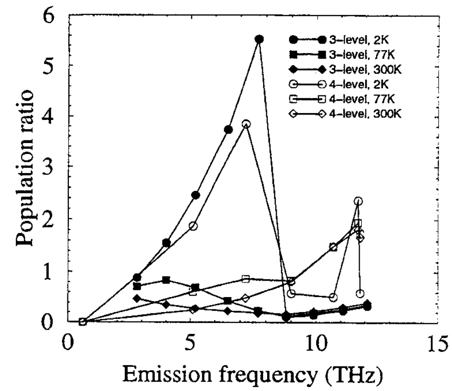

Fig. 7. The population ratio at temperatures of 2, 77, and 300 K for both the 3-level and 4-level systems as a function of emission energy

temperatures and indeed do rise above 1 at the higher terahertz frequencies—thus room temperature stimulated emission is a possibility.

C. *Electrically excited lasers*

The final stage of the design of terahertz sources is the electrically injected laser, this is the subject of another work in these proceedings[13].

IV. Conclusion

It has been shown that energy levels of semiconductor quantum well systems can be engineered to provide energy separations in the terahertz region of the spectrum. The potential for emitters and optically excited lasers has been evaluated from the basis of the electron scattering properties. It has been shown that a superlattice could provide tunable emission at around 8 THz albeit at low temperature. Asymmetric quantum wells have been shown to fulfil the electron dynamical criteria to exhibit population inversion at room temperature for emission around 10 THz.

Acknowledgments

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