Electrical generation of terahertz electromagnetic pulses by hot-electrons in quantum wells

W. Xu, S. M. Stewart, D. J. Fisher, C. Zhang
Department of Physics, University of Wollongong, Wollongong, New South Wales 2522, Australia

(Received 15 July 1996)

We present a theoretical study on the electrical generation of terahertz (THz) electromagnetic pulses by hot-electrons in AlGaAs/GaAs-based two-dimensional semiconductor systems (2DSSs). The intensity of THz blackbody radiation has been calculated as a function of photon frequency and electron temperature. We consider that the electrons are heated by pulsed electric fields and that the hot-electron interactions with electromagnetic fields are mediated by electron–phonon scattering.

Key words: electromagnetic emission, hot-electron, quantum well.

1. Introduction

In recent years, the generation, propagation and detection of terahertz (THz) electromagnetic radiations has become one of the most important research fields in both optoelectronics and semiconductor physics, because of their significant impact on far-infrared (FIR) spectroscopy and on the characterisation of low-dimensional semiconductor systems (LDSSs). Under the action of electric and/or magnetic fields, the energy transfer in a LDSS during the electronic transitions, due to scattering, etc. will reach the meV scale. The processes of the electronic transition may be accompanied by the emission and/or absorption of the THz photons. Optical generation of THz electromagnetic radiations from AlGaAs/GaAs-based two-dimensional semiconductor systems (2DSSs) has been studied rather extensively in recent years [1–5]. In some practical device applications, it is desirable to be able to generate electrically the THz electromagnetic pulses. It has been realised that using AlGaAs/GaAs-based 2DSSs, the THz radiations can be generated electrically via mechanisms such as blackbody radiation [6, 7], FIR cyclotron emission [8], hot-plasmon emission [9], tunnelling-assisted THz laser generation [10], etc. The results obtained from recent experimental measurements [7–9] have indicated that hot-electrons can play a very important role in generating electrically THz electromagnetic waves from 2DSSs. The theoretical results for optically spontaneous emission by free electrons are well known and well documented [11, 12]. However, little theoretical work regarding electromagnetic generation by hot-electrons in 2DSSs has been reported. The motivation of the present study is to attempt a contribution in this direction.

2. Theoretical model

The electrons in a 2DSS can be heated by, e.g. a pulsed electric field and a two-dimensional electron gas (2DEG) at a temperature $T_e$ is expected to emit blackbody radiation. From the theoretical point of view, the
where \( E \) depending on the electronic state dependent only on \( \lambda \).

For electromagnetic radiation from a 2DSS in the THz frequency regime, the electronic transition where electron interactions with impurities, phonons, etc. is on the scale of the radiation frequency [14, 15]. One therefore must take into account depletion of the initial state \([k, n]\) to a state \([k', n']\) is given by [11]

\[
L[k, n; E_n(k') - E_n(k) \mp \hbar \omega] = \frac{1}{\pi} |E_n(k') - E_n(k) \mp \hbar \omega|^2 + \frac{\hbar \lambda_n(k)/2}{\hbar \lambda_n(k)/2}.
\]

Here \( \lambda_n(k) \) is the scattering rate for the initial state induced by electron interactions with impurities, phonons, etc. We note that in contrast to most published papers [11, 16] where \( \lambda_n(k) \) is taken to be a constant or dependent only on \( n \), inclusion for the effect of depletion of electronic states requires a scattering factor depending on the electronic state \([k, n]\).

After (i) following the usual treatment for electron–photon interactions [12] using a dipole approximation; (ii) employing a Fermi–Dirac type of statistical energy distribution function as an electron distribution through \( f_E(k) = f(E_n(k)) \) where \( f(x) = (1 + e^{\frac{x-E_F}{k_B T}})^{-1} \). Here \( E_F \) the Fermi energy while \( T_F \) the electron temperature; and (iii) noting that electron–phonon scattering in a 2DSS is isotropic [15], then \( \lambda_n(k) = \lambda_n(E) \) where \( E = \hbar^2 k^2/2m^* \), the intensity of electromagnetic radiation per unit time for a 2DSS is then obtained from

\[
P(\omega) = [N(\omega) + 1]I^-(\omega) + N(\omega)I^+(\omega).
\]

Here \( N(\omega) = (e^{-\hbar\omega/\hbar T} - 1)^{-1} \) is the photon occupation number and

\[
I^\pm(\omega) = \frac{8\epsilon^2 u_c^2}{m*\omega_0 V} \sum_{\neq n}(\epsilon_n - \epsilon_n) G_{nn} \int_0^\infty dE \frac{f(E + \epsilon_n)[1 - f(E + \epsilon_n)]A_n(E)}{(\epsilon_n - \epsilon_n \mp \hbar \omega)^2 + A_n^2(E)},
\]

with \( u_c \) the component of the polarization vector in the z-direction (growth direction), \( V \) the volume of the sample device, \( G_{nn} = \int dz \psi_n^*(z)[d\psi_n(z)/dz]^2 \) and \( A_n(E) = \hbar \lambda_n(E)/2 \). From eqn (4), we see that: (i) the electromagnetic wave is generated mainly through inter-subband scattering processes accompanied by electronic transitions around the Fermi level; and (ii) the polarization of the electromagnetic wave generated is along the z-direction.

For a practical calculation, below, we study blackbody radiation by hot-electrons in AlGaAs-GaAs-AlGaAs single quantum wells (SQWs) in which we have

\[
G_{nn} = \frac{4n^2\pi^2}{(n^2 - n^2)^2} \frac{1 - (-1)^{n+n}}{L^2}.
\]
Fig. 1. Intensity of electromagnetic radiation from a single quantum well as a function of photon frequency at a fixed lattice temperature \( T \) for different electron temperatures \( T_e \). \( L \) and \( n_e \) are the width of the well layer and electron density of the 2DEG, respectively.

Fig. 2. Influence of electron density on the THz radiation generated from a SQW at a fixed lattice and electron temperature. The results are shown for: \( n_e = 3 \times 10^{16} \text{ m}^{-2} (\cdots\cdots), 10^{16} \text{ m}^{-2} (-----), 5 \times 10^{15} \text{ m}^{-2} (\cdots\cdots\cdots) \) and \( 2 \times 10^{15} \text{ m}^{-2} (\cdots\cdots) \).

Here \( L \) is the width of the well layer. It implies that the radiation takes place only when \( n' + n = 2N + 1 \) \((N = 1, 2, \ldots) \) is satisfied. When the photon emission occurs in the hot-electron regime, the electron interaction with longitudinal-optic (LO) phonons is the principal channel to scatter the electrons. The scattering rate for electron–LO-phonon interaction in a SQW has been documented by Ref. [15].

3. Results and discussion

The intensity of electromagnetic radiation from a SQW at a fixed lattice temperature increases rapidly with electron temperature (see Fig. 1). At low excitation levels \((T_e < 50 \text{ K})\), the radiation has a relatively weak dependence on the frequency. At relatively high excitations \((T_e > 50 \text{ K})\), a peak in the radiation emission can be observed around THz frequencies \( \omega_p = (\varepsilon_2 - \varepsilon_1)/\hbar \). It has been implied by eqn (6) that the electromagnetic wave is mainly generated between the subbands \( n = 1 \) and 2. Increasing the electron density \( n_e \) will result in an increase in the background radiation (see Fig. 2). The results shown in Fig. 3 indicate that varying the lattice temperature will lead to a variation of the radiation generation in the low-frequency regime \((\omega < \omega_p)\),
and the high-frequency radiation \((\omega > \omega_p)\) depends weakly on the lattice temperature. This implies that a 2DSS at temperature \(T_e\) will emit high-frequency radiation of equivalent temperature \(T_e\).

The frequency dependence of electromagnetic radiation from SQWs with different widths of the well layer is shown in Fig. 4. The peak in the radiation spectrum shifts to a higher frequency for a smaller quantum well width because \(\varepsilon_n \sim L^{-2}\) increases with decreasing \(L\) for a SQW. The intensity of radiation around \(\omega_p\) decreases with \(L\), which implies that a stronger electromagnetic generation can be observed in the devices with relatively larger well widths. We see that the frequency-tunable THz electromagnetic pulses can be generated using the structure of AlGaAs-GaAs-AlGaAs SQWs with different widths of the quantum well.

4. Conclusions

The theoretical results presented in this paper have demonstrated that AlGaAs/GaAs-based two-dimensional semiconductor systems can be used as devices for generating THz pulses by, e.g. electrically heating the electrons in the structure. In the hot-electron regime, the rate of electron energy relaxation via interactions with impurities, phonons, etc. is also on the THz scale. Thus electronic transitions may be accompanied by
processes of emission and absorption of electromagnetic radiation in the THz frequency regime. Blackbody radiations from a 2DSS is mainly generated through the inter-subband scattering channels.

Acknowledgement—This work is supported by the Australian Research Council.

References