Far-Infrared Electroluminescence in Parabolic Quantum Wells

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We have measured the far-infrared emission from parabolically graded quantum wells driven by an in-plane electric field in the temperature range from 20 K to 240 K. The peak emission corresponds to the intersubband plasmon in the parabolic potential. Its photon energy (6.6 meV / 9.8 meV) remains rather unaffected by temperature variations, the full width at half maximum ranges from 1 meV (T = 20 K) to 2 meV (T = 240 K). The reduction of emission efficiency with increasing temperature is attributed to the change in the non-radiative lifetime.

1. Introduction

The need for solid state far-infrared sources operating without a magnetic field has stimulated the research on intersubband electroluminescence in semiconductor heterostructures. Experiments have been performed on parabolic quantum wells [1], on superlattices [2], and more recently on quantum cascade structures [3], [4].

Parabolically graded quantum wells are promising candidates for far-infrared sources operating above liquid nitrogen temperature. The large temperature-induced variation of the electron distribution is expected to have little impact on the emission performance. In accordance with the generalized Kohn´s theorem [5] the emission frequency is independent of the electron distribution and concentration in the well. In absorption and emission spectroscopy coupling between the radiation and the electron system has been observed at only one frequency [6], [1]. This is the harmonic oscillator frequency, solely determined by the width and the energetic depth of the quantum well. Here, we demonstrate the stability of the intersubband emission in a parabolic quantum well up to a temperature of 240 K [7].

2. Experimental

Two samples were examined: one with 140 nm, the other one with 200 nm well width, both with 167 meV energetic well depth. Figure 1 shows the layer structure and the device geometry of the 140 nm well sample schematically. The samples were grown by molecular beam epitaxy, depositing alternate layers of $Al_{0.3}Ga_{0.7}As$ and GaAs on a semi-insulating GaAs substrate. By adjusting the ratio of the layer thicknesses, the average Al-content in the well region is parabolically graded from x = 0 to x = 0.2. The well is sandwiched between $Al_{0.3}Ga_{0.7}As$ spacer layers and remotely doped. The sample was contacted with two parallel AuGe Ohmic contact stripes. In order to couple out the intersubband radiation that is polarized with its electrical field perpendicular to the layers a metallic CrAu grating was evaporated between the contacts. A more detailed description of the 200 nm well sample had been given elsewhere [1].

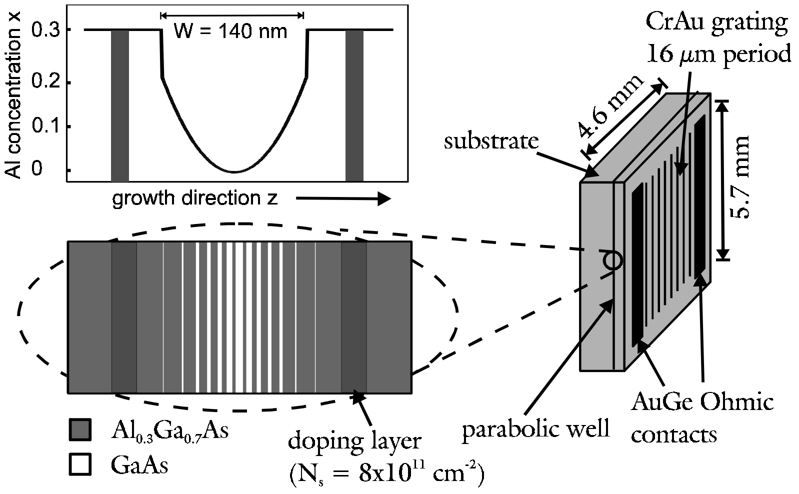

Fig. 1: Layer structure and sample geometry of the 140 nm well sample.

We measured the electroluminescence using a Fourier-transform infrared spectrometer in step scan /lock-in mode with a spectral resolution of 0.5 meV. The sample was mounted on the cold finger of a helium-flow cryostat. The emitted radiation was collected by an off-axis parabolic mirror, transmitted through the spectrometer, and then focussed on a helium cooled Si bolometer. The whole beam path was purged with dry nitrogen gas to minimize the far-infrared absorption of water vapor. In order to excite the electron gas a pulsed electric field at a frequency of 411 Hz and 50 % duty cycle was applied between the Ohmic contacts.

3. Results

In Fig. 2 a, spectra of the 200 nm well at various temperatures are displayed. The peak emission is observed at a photon energy of 6.6 meV for all temperatures. This value corresponds to the harmonic oscillator energy calculated from the well dimensions as 6.0 meV. In agreement with the generalized Kohn´s theorem, the emission energy is unaltered by the temperature-induced variation of the electron distribution in the well. The spectra of the 140 nm well in Fig. 2 b show a 20 K emission peak at 9.8 meV (calculated as 8.4 meV) that is slightly shifted to lower energies (9.1 meV) as the temperature is raised to 240 K. The full width at half maximum of the emission line of both samples ranges from 1 meV at low temperatures to 2 meV in the high temperature regime (T > 100 K). The temperature dependence of the optical power collected by the bolometer P_{co} of both samples is depicted in the inset of Fig. 2. It was determined as the integrated area of the emission spectra divided by an amplification factor and the bolometer responsivity.

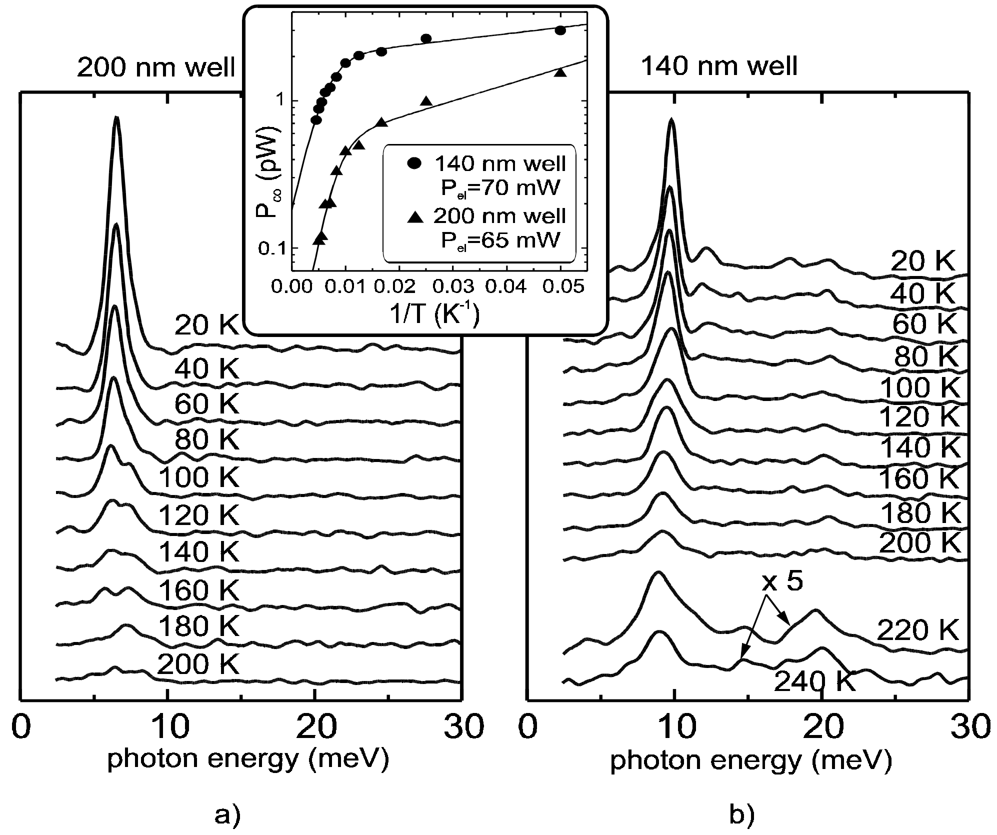

Fig. 2: Emission spectra of the two samples for various temperatures as indicated. The inset shows the dependence of the collected optical power P_{co} on the inverse temperature 1/T.

The collected optical power Pco is assumed to depend on the electrical input power P_{el} and on the ratio of non-radiative lifetime τ_{nr} and radiative lifetime τ_r (in case of $\tau_r >> \tau_{nr}$) like

$$P_{co} \propto P_{el} \frac{\tau_{nr}}{\tau_r} .$$

The proportionality between the collected optical power P_{co} and the electrical input power P_{el} has been confirmed up to ~70 mW, above which saturation occurs. The difference in the optical power P_{co} between the two samples can be qualitatively understood by looking at the radiative lifetime τ_r. It was calculated in the model of a classical electron oscillator as 59 µs for the 140 nm well and 130 µs for the 200 nm well. With the simplifying assumption of similar non-radiative lifetimes, grating-coupler efficiencies and excitation efficiencies, one would expect the optical power P_{co} of the 140 nm well sample to be approximately twice the one of the 200 nm well sample at comparable electrical input powers P_{el}.

The decrease of (collected) optical power is induced by a thermally activated process. The solid lines in the inset of Fig. 2 are fits of the inverse sum of two exponential functions in 1/T yielding activation energies of E_1 = 34 meV, E_2 = 0.8 meV for the 140 nm well sample and E_1 = 41 meV, E_2 = 2.2 meV for the 200 nm well sample. The higher energy E_1 is probably the activation barrier for the emission of optical phonons. The intersubband transition rate 1/ τ_{nr} shows a similar behavior of thermal activation, as described by Heyman et al. [8]. We may deduce that the temperature dependence of the optical power is governed by the non-radiative lifetime τ_{nr}. At temperatures above ~100 K, the emission of optical phonons limits the optical power.

4. Conclusion

We have demonstrated electrically driven far-infrared emission of parabolic quantum wells up to a temperature of 240 K. At high temperatures, the thermal energy k_BT exceeds the photon energy by a factor greater than two. Despite of the large temperature related shift of the electron distribution, we observe single frequency emission, and the impact of high temperatures on the frequency and the line shape is small. The emission efficiency is limited by the temperature dependent decrease of intersubband lifetime.

Acknowledgements

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