Extended Abstracts of the 1999 International Conference on Solid State Devices and Materials, Tokyo, 1999, pp. 418–419 **D-9-4**

Mid-Infrared Detection and Fano Resonance in Bound-to-Continuum Intersubband Transition in Self-Assembled InAs Quantum Dots

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1. Introduction

The quantum dot infrared photodetectors (QDIPs) using InAs self-assembled quantum dots (QDs) have been proposed and successful operation in the mid-infrared range has been demonstrated [1,2]. Most of the structures reported so far utilize a vertical transport through stacked self-assembled QDs. However, it is difficult to obtain high photoconductive gains in the vertical transport structures because of unavoidable inhomogeneity in size and spatial alignment of the self-assembled QDs.

2. Experiments

We have designed and fabricated a QDIP which utilizes the bound-to-continuum intersubband transition in the self-assembled InAs QDs and subsequent lateral transport of photoexcited carriers in the modulation-doped AlGaAs/GaAs two-dimensional (2D) channel. 10 InAs SAQD layers were grown at 470 °C on (001) semi-insulating GaAs substrates by molecular beam epitaxy. Each layer was embedded in the middle of 100 nm-thick GaAs quantum wells. The 30 nm-thick AlGaAs barriers were δ-doped with Si up to 1×10^{11} cm^{-2}. The essential points of the structure are ; 1) the size of the InAs QDs is made small to accommodate only one bound state in the QDs by adopting low temperature growth, 2) high-mobility modulation-doped AlGaAs/GaAs heterointerfaces are used as the conducting channels for photoexcited carriers, and 3) a long carrier lifetime is achieved by using a large distance between the QDs and the heterointerfaces. The electrons are photoexcited from the ground state in the QDs to the virtual excited state in the conduction band of GaAs (bound-to-continuum intersubband transition), relax to the heterointerface, and drift laterally along the interface due to the applied electric field, thereby producing a photocurrent (Fig. 1).

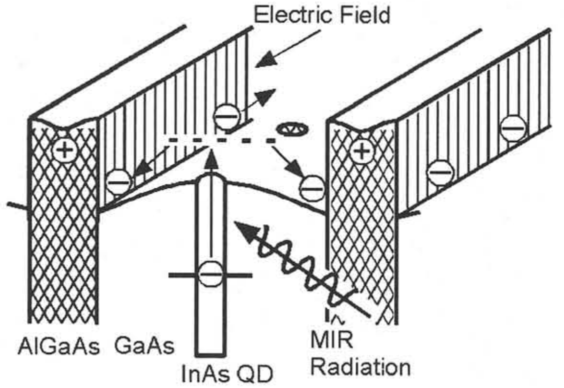

Fig. 1 The schematic band diagram of the modulation-doped QDIP structure.

3. Results and Discussion

The photocurrent spectra of the QDIP were measured in a single-pass normal incidence geometry by using a Fourier transform spectrometer. A broad photosignal is observed for the normal incidence radiation in a photon energy range of 100-300 and even above 400 meV as shown in Fig. 2. It should be noted that the obtained sensitivity spectrum shows a Fano profile; a large peak accompanied by a well resolved quasi-loss of signal.

It is well known in the atoms that the states in the continuum keep the memory of the discrete states, so called "resonance" [3]. A similar behavior should take place in the case of the InAs/GaAs QDs.

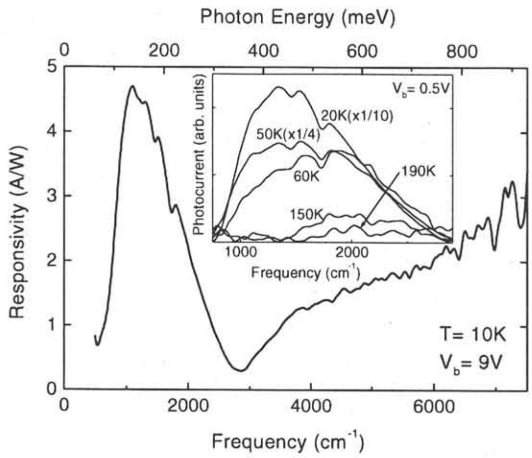

Fig. 2 The photocurrent spectrum measured in a single-pass normal incidence geometry with $V_b = 9$ V at $T = 10$ K. The inset shows the photocurrent spectra measured with V_b = 0.5 V at various temperatures.

To understand the interplay between the discrete state and the continuum we have developed a qualitative approach based on the initial model of the optical intersubband transition. The photon-electron coupling is treated at the dipolar approximation and the shape of the dot is modeled by a flat cylinder. Within this approximation it becomes possible to calculate analytically both the energy spectrum and the associated probability of intersubband transition. The result is shown in Fig. 3 and displays a similar behavior with the experimental data: an enhancement of the probability of intersubband transition at 200 meV and quasi-loss of signal at around 350meV.

A peak responsivity as high as 4.7 A/W was obtained experimentally at $h\nu = 160$ meV at $T = 10$ K. This value is approximately two orders of magnitude larger than the values for the QDIPs reported so far [1]. The high responsivity is realized mainly by a high mobility and a long lifetime of photoexcited carriers in the modulation-doped 2D channels. Furthermore, it is found that the observed photosensitivity survives up to 190 K, as shown in the inset of Fig. 2.

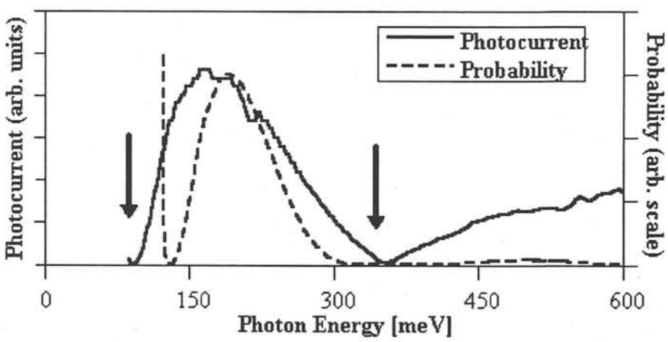

Fig. 3 The photocurrent measured at T = 20 K (solid line) and the calculated probability of intersubband transition from the ground state in the QD to the continuum states (broken line) (QD : height 1 nm - radius 9 nm).

4. Conclusions

We have fabricated a QDIP which utilizes the bound-to-virtual state intersubband transition in the self-assembled InAs QDs and subsequent lateral transport of photoexcited carriers in the modulation-doped 2D channel. A broad photosignal is observed in a photon energy range of 100-300 meV and even above 400 meV, which originates from the bound-to-continuum intersubband transition from the localized bound states in the QDs to the resonant virtual states in the continuum. A peak responsivity as high as 4.7 A/W was obtained.

References

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[3] See, for example, Franz Schwabl, *Quantum Mechanics*, Springer (1995).