Simulation on a Charge Sensitive Infrared Phototransistor for 45µm Wavelength

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Abstract — Charge sensitive infrared phototransistors (CSIP) are well known for their capability for response spectrum tuning and single photon detection. In this paper, we established a physical model for a charge sensitive infrared phototransistor operating at 45µm wavelength using the Crosslight Apsys software. Several key physical mechanisms involved such as inter-subband optical transition and resonant tunneling of carriers were applied and fine tuned to obtain a better simulation result.

Keywords – charge sensitive infrared phototransistor, 2DEG, quantum well ,single-photon detection, Apsys;

I. Introduction

Single-photon detection in the long wavelength range has been a very important field, where only semiconductor quantum well (QW) and quantum dot (QD) devices are potential candidates due to their high sensitivity as well as their abilities to tune response wavelength range by adjusting parameters such as potential barrier height and quantum well width. Recent years have seen increasing studies of Charge Sensitive Infrared Phototransistors (CSIPs) that are ultrasensitive and with possible terahertz (THz) wavelength detection. Unlike the traditional QW infrared photo-detectors, a typical CSIP device assembles QW structure and two dimensional electron gas (2DEG) together for more efficient light detection. Under proper light illumination, electrons generated by inter-subband transition in the isolated upper QW will tunnel out of the QW and migrate to the lower 2DEG [1]. Several experiments have been conducted to demonstrate CSIPs' single photon detection capability [2-4], but theoretical simulations of these devices on the microscopic scale are inadequate.

Previous simulation results on a novel CSIP structure for 15µm wavelength have been reported [5]. In this paper, we adjusted the structure of a CSIP device using Crosslight Apsys software and by constructing the model based on inter-subband transition and resonant tunneling, we successfully extended its working wavelengths to 45µm region.

II. Modeling

The device for 45µm was constructed according to Ref [6]. As shown in Fig. 1(a), it consisted of a 500-nm-thick GaAs buffer at the bottom, a 210-nm-thick $Al_{0.3}Ga_{0.7}As$/GaAs superlattice barrier, a 10-nm-thick Si-doped ($10^{18}cm^{-3}$) $Al_{0.3}Ga_{0.7}As$ layer, a 20-nm-thick $Al_{0.3}Ga_{0.7}As$ spacer layer, a 150-nm-thick $Al_{0.04}Ga_{0.96}As$ layer, a 2-nm-thick $Al_{0.1}Ga_{0.9}As$ barrier layer, a 20-nm-thick Si-doped ($2.5x10^{17}cm^{-3}$) GaAs upper QW layer, a 35-nm-thick $Al_{0.3}Ga_{0.7}As$ barrier layer, a 55-nm-thick Si-doped ($10^{18}cm^{-3}$) $Al_{0.3}Ga_{0.7}As$ layer and 10-nm GaAS cap layer on the top. The lower 2DEG was formed at the interface between the 150-nm-thick $Al_{0.04}Ga_{0.96}As$ layer and the 20-nm-thick $Al_{0.3}Ga_{0.7}As$ spacer layer. Fig. 1(c) is the cross-sectional view of the device. Ohmic contacts were made to connect the upper QW and the lower 2DEG. Meanwhile two Schottky gates were deposited to isolate the upper QW when negatively biased. And a rectangle shaped aperture ($100x50\mu m^2$) was left on the top for optical access. Fig. 1(b) is the conduction-band diagram simulated when the device is at thermal equilibrium.

Considering the optical inter-subband transition, we first established a separate model of the upper QW in order to get its absorption spectrum. In Apsys software, all possible inter-subband transitions between all the energy levels were evaluated and integrated to compute the absorption spectrum [7-8]. Figure 2 and figure 3 are the simulated band structure and the absorption spectrum of the upper QW respectively. It showed a peak at nearly 45µm wavelength reaching about $1.4X10^5cm^{-1}$, which is consistent with the target detection

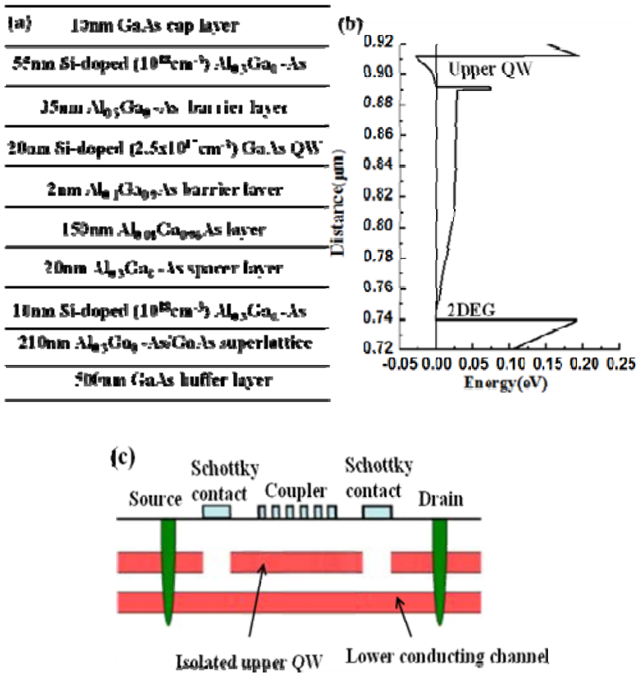

Fig.1.(a) The schematic diagram of the charge sensitive infrared phototransistor for 45µm. (b) The conduction-band diagram simulated at thermal equilibrium. (c) The cross-sectional view of the device from Ref [7].

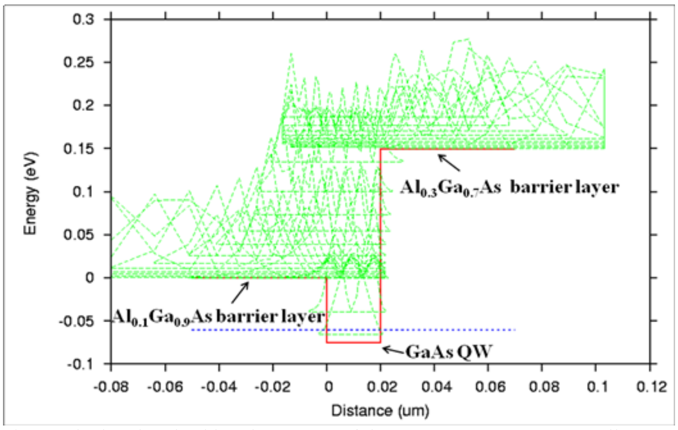

Fig. 2. The band and subband structure of the upper GaAs quantum well.

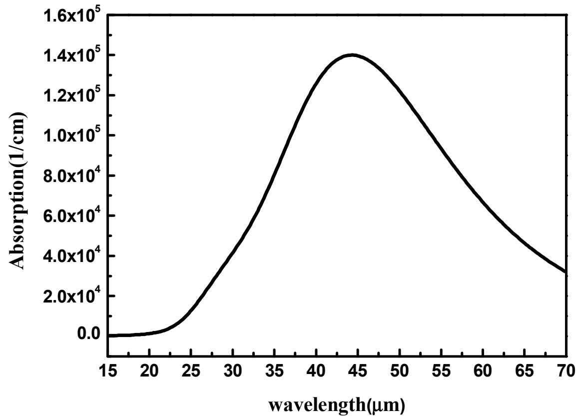

Fig. 3. The absorption spectrum profile of the upper GaAs quantum well.

wavelength. For the subsequent simulation, the absorption spectrum profile was imported to calculate the excitation electrons in the upper QW layer.

III. RESULTS AND DISSCUSSION

The simulation result of source-drain conductance (G_{sd}) as a function of the Schottky gates voltage (V_g) without light illumination is shown in figure 4. The source-drain bias voltage (V_{sd}) was set to be 5mV. In dark condition, G_{sd} declined as V_g decreased, and completely vanished at -0.54V. Negative bias on the Schottky gates increased the depletion beneath and isolated the layers in sequence. Under -0.54V, all layers connected to the ohmic contacts were depleted and no current flew.

To simulate the I-V property of the device, we added a light illumination of 45μm in wavelength and $2x10^{-2}W/m^2$ in power. Resonant tunneling model was also applied in order to get a more accurate simulation result.

The inset in figure 4 plots the G_{sd} versus V_g under illumination between -0.51V and -0.45V. In this region, the upper QW was completely isolated as shown in Fig. 1(c). Electrons generated in the upper QW tunneled out of the thin 2 nm $Al_{0.1}Ga_{0.9}As$ barrier layer, and moved to the 2DEG below yielding photo-currents. Meanwhile, the missing electrons made the isolated upper QW pile up large amounts of holes,

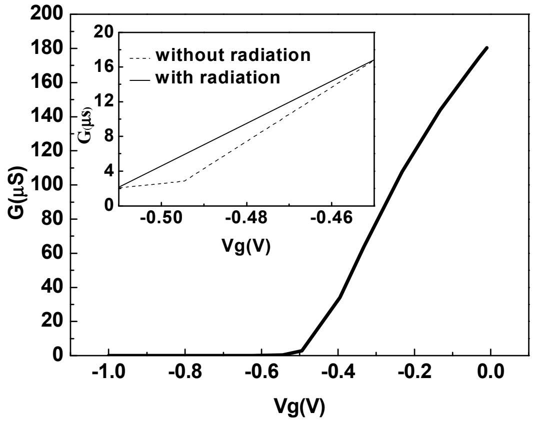

Fig. 4. The source-drain conductance (G_{sd}) versus Schottky gates voltage (V_g) without light illumination.

which affected the conductance of the lower 2DEG. Response under such a weak illumination can be found. Compared with the experimental measurements in Ref [6], the discrepancy in the device responsivity of our computed result can be attributed to the temperature used in our simulation. The experiment in Ref [6] was conducted at 4.2K, whilst in our simulation the lowest temperature allowed was limited by the software. This result further demonstrated CSIP's potential in detecting long wavelength and ultra-weak light signals.

IV. CONCLUSION

We successfully constructed a physical model of a CSIP for 45μm wavelength. The simulated result shows its potential in detecting long wavelength and ultra-weak light signals.

ACKNOWLEDGMENT

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