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Characteristics of InGaAs quantum dot infrared photodetectors

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A quantum dot infrared photodetector (QDIP) consisting of self-assembled InGaAs quantum dots has been demonstrated. Responsivity of 3.25 mA/W at 9.2 μm was obtained for nonpolarized incident light on the detector with a 45° angle facet at 60 K. The QDIPs exhibit some unique electro-optic characteristics such as a strong negative differential photoconductance effect and blueshift of the response peak wavelength. © *1998 American Institute of Physics.* [S0003-6951(98)01547-2]

Quantum well infrared photodetectors (QWIPs) utilizing intersubband transitions have been widely investigated during the past several years due to clear commercial and military applications (see, for example, one recent review article by Levine[1]). Very recently, the mid- and far-infrared absorption[2–6] and photoconductivity[7,8] in self-assembled InAs and InGaAs quantum dots have been reported. A so-called quantum dot infrared photodetector (QDIP) was proposed and considered theoretically by Ryzhii.[9] In this theoretical work, better performance such as low dark current, high photoelectric gain, and sensitivity of the QDIP as compared to QWIP were predicted. In this letter, we report the characteristics of self-assembled $In_{0.35}Ga_{0.65}As$ QDIPs. To the best of our knowledge, we believe the present work provides the first demonstration of self-assembled quantum dots as efficient mid- and far-infrared detectors.

The self-assembled $In_{0.35}Ga_{0.65}As$ quantum dots used in the present study were grown in a GaAs matrix by molecular beam epitaxy in the Stranski–Krastanow (S–K) growth mode. The whole structure was grown on semi-insulating GaAs (100) substrates. The main structure of the detectors consists of 20 periods of $In_{0.35}Ga_{0.65}As$ quantum dot layers separated by 30 nm GaAs barrier layers. The InGaAs dot layers were uniformly and directly silicon doped. The Si doping density was 6×10^{17} cm^{-3} to provide approximately one dopant atom per dot. The detailed growth processes have been described elsewhere.[10] The low-temperature photoluminescence, infrared absorption, and cross-sectional transmission electron microscopy of the Si-doped $In_{0.35}Ga_{0.65}As$ quantum dots (QDs) can be found in another of our papers.[6]

The devices were fabricated into mesa diodes of 200 $\times$200 μm^2 using standard photolithography techniques, contact metal evaporation, and wet chemical etching. The dark current–voltage characteristics of the QDIPs were measured using a HP4156A precision semiconductor parameter analyzer. The spectral dependence of their photoresponse was measured using a ceramic infrared source coupled to an Oriel MS257 monochromator with lock-in detection.[11] Due to the strong dependence of the infrared absorption strength on the polarization angles of the infrared incident light,[6] the infrared light was illuminated on the mesa with a 45° facet polished on the wafer in order to enhance the coupling between infrared radiation and the bound electrons in the quantum dots. That is, the geometry for the measurement of the QDIP optical response is very similar to the commonly used geometry for the QWIP.[1] In the low-temperature measurements, the devices were mounted on the cold finger of a 10 K CTI-Cryogenics cryostat system.

Figure 1 shows the measured dark current–voltage curves of the detectors at different temperatures. Similar to the dark current–voltage characteristic of the InGaAs QWIP,[1] the dark current of the QDIP increases rapidly with temperature. Accordingly to Ryzhii's model,[9] the rapid increase of the dark current of the QDIP with temperature is mainly due to its exponential dependence on temperature. Like the case of the QWIP, the main mechanism producing the dark current in the QDIP devices is still the thermionic emission of the electrons confined in the quantum dots. In

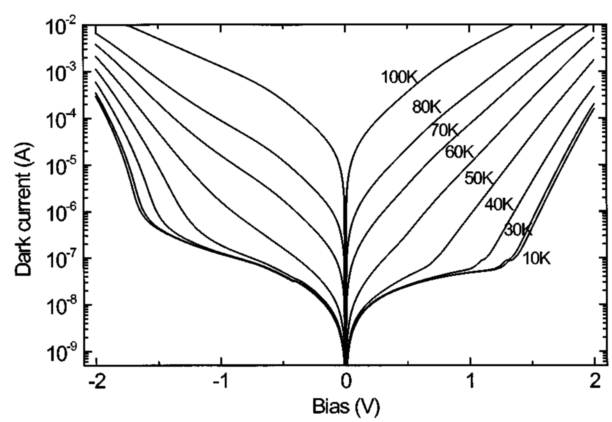

FIG. 1. Measured dark current–voltage characteristics for InGaAs QDIP at different temperatures.

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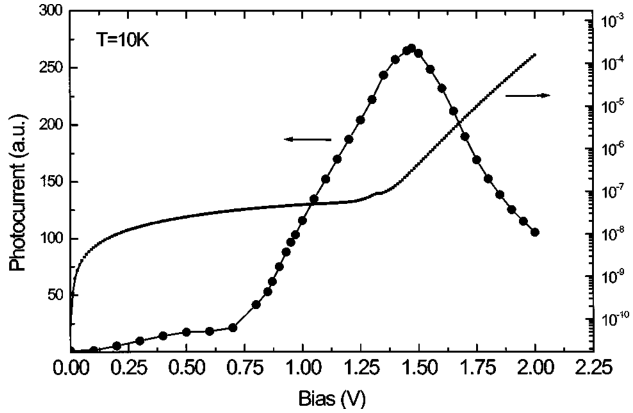

FIG. 2. 10 K dark current and photocurrent of the device as a function of the applied forward bias. The excitation light is 9.18 μm nonpolarized infrared radiation from the ceramic source for the photocurrent measurement.

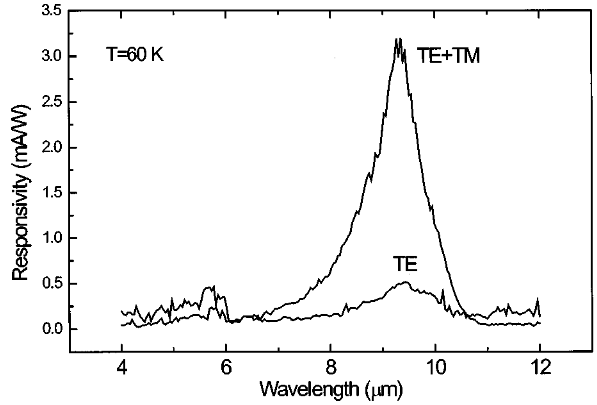

FIG. 3. Measured responsivity wavelength spectra at 60 K for two different polarization lights. Infrared is incident from the 45° polished facet on the detector.

order to give more information on the transport mechanism of the QDIPs, the dark current and photocurrent at 10 K are shown in Fig. 2 as a function of forward bias. The so-called forward bias means that the top contact of the device is biased positively. The illumination light is nonpolarized infrared of 9.18 μm wavelength during the measurements of the voltage dependence of the device photocurrent. From the features of the dark current– and photocurrent–voltage curves in Fig. 2, it can be seen that a threshold voltage of about 0.6 V seems to exist. When the applied bias exceeds this threshold voltage, both dark current and photocurrent increase exponentially. This is likely in agreement with the theoretical prediction.[9] In Ryzhii's theoretical QDIP model, a special voltage V_m has been predicted. If the applied bias is over V_m, both the dark current and the photocurrent exhibit exponential dependence on the applied voltage. The increase of the photocurrent with the applied voltage means that the QDIP responsivity is also a growth function of the voltage. However, we found that the measured photocurrent of the QDIPs is not a monotonic increasing function of the applied voltage. When the applied bias is at 1.46 V, the photocurrent reaches its maximum value. With further increase of the applied voltage the photocurrent starts to decrease, showing a striking negative differential photoconductance. At the same time, the dark current increases significantly with bias. Choi *et al.*[12] observed the negative differential photoconductance phenomenon in an alternatively doped multiple-quantum-well structure. They attributed the observed negative differential photoconductance to the high electric-field domain effect. The local high electric-field domain results in resonant filling of electrons in the undoped quantum wells. Thus, there is a maximum in the density of electrons in the undoped wells at a certain bias, inducing a maximum in the responsivity or photocurrent. However, understanding of the negative differential photoconductance observed in the QDIPs needs further theoretical and experimental investigation. We will discuss this interesting phenomenon in detail elsewhere.

Figure 3 shows the photoresponse spectra of the QDIP at 60 K for two polarizations of the incident infrared light. In order to obtain the responsivity, the photon flux intensity as a function of wavelength was measured simultaneously using a calibrated pyroelectric detector.[11] For unpolarized infrared light we have observed a responsivity of 3.25 mA/W at about 9.2 μm and for the light incident normal to the structure the responsivity was about 0.5 mA/W. For TM mode polarized light the measured responsivity at 60 K was about 5.0 mA/W. The responsivity ratio between TE mode (also called *S* polarization) and TM mode (also called *P* polarization) infrared light is about 10%. However, if the inevitable light scattering by device edges or other rough features on the detector[13] is taken into consideration, we believe the photoresponse of the QDIPs for the *S* polarization incident light is still very small. Moreover, the room-temperature infrared absorption measurements for the InAs and InGaAs self-assembled QDs show no obvious absorption for the *S* polarization light.[6]

Figure 4 shows the responsivity wavelength spectra of the QDIP at 30 K for different applied forward bias. The maximum responsivity at 30 K is close 80 mA/W, which is over 20 times more than that at 60 K. When the bias is below about 1.46 V the responsivity increases with increasing applied voltage. After the bias is beyond 1.46 V the responsivity decreases. That is a replica of the negative differential photoconductance observed in Fig. 2. Another feature of the applied electric-field dependence of the photoresponse spectra in Fig. 4 is the blueshift of the photoresponse peak. That is, the peak position shifts to higher energy with increasing applied electric field. So far, very few theoretical and experimental investigations on the topic of the electric-field depen-

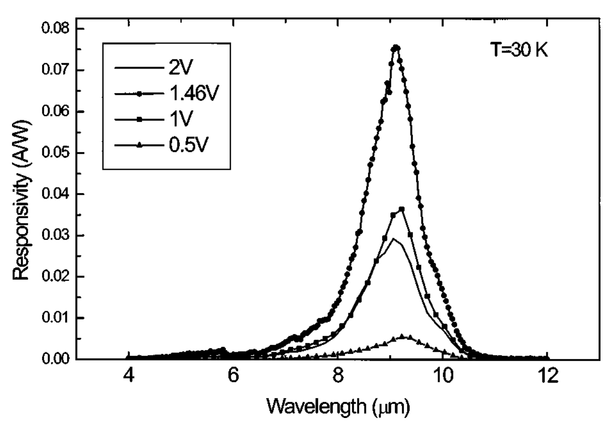

FIG. 4. 30 K responsivity spectra of the detector at different applied voltages for nonpolarized incident light.

dence of the intersubband transition in QDs have been reported. The result should, therefore, serve as the starting point for further exploration on this topic.

The existence of wetting layers in the self-assembled QDs grown in SK mode causes some arguments on the infrared absorption and thus photoconductivity resulting from transitions out of the QDs. The increasingly powerful experiments[2–8] from different laboratories in the world have confirmed the strong intersubband transitions in the QDs. The selection rule of the transitions in the self-assembled QDs and their device application development will be the next study focus.

In conclusion, the characteristics of InGaAs/GaAs self-assembled quantum dot infrared photodetectors were reported. The present nonoptimized detector gave a maximum responsivity of about 3.25 mA/W at 60 K and 80 mA/W at 30 K, respectively. Strong negative differential photoconductance was observed. Demonstration of the QDIP, we believe, will push the development of self-assembled QDs as efficient mid- and far-infrared detectors and emitters.

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