World of Knowledge

Quantum-Dot/Quantum-Well Mixed-Mode Infrared Photodetectors

Assistant Research Fellow Shih-Yen Lin
Postdoctoral Research Fellow Shu-Ting Chou
Research Center for Applied Sciences

GaAs/AlGaAs quantum-well infrared photodetectors (QWIPs) have attracted intensive attention since 1980s. Due to the possible bandgap engineering for the GaAs/AlGaAs materials, various kinds of GaAs/AlGaAs QWIPs have been developed. The detection wavelengths of the QWIPs could extend from 6 to 25 μm. Single-color, multi-color and voltage-tunable multi-color QWIPs have been successfully developed. Due to that GaAs and AlGaAs materials are lattice-matched, high-quality epi-wafers could be obtained either by molecular beam epitaxy (MBE) or metal-organic chemical vapor-phase deposition (MOCVD) techniques. Therefore, in 1995, the first 128 x 128 QWIP focal-plane array (FPA) had been developed by Jet Propulsion Laboratory (JPL). FPAs with larger formats like 256 x 256 or 640 x 480 have also been developed with the mature fabrication technique. Due to the wide detection window and high wafer uniformity of the devices, huge applications have been developed either in military or civil areas. Although QWIPs are of all the advantages discussed above, the major drawback of the device is its low-temperature operation requirement (<77 K). The limitation has made high-temperature operation and easy-to-carry property of the device less possible to achieve. Compared with QWIPs, quantum-dot infrared photodetectors (QDIPs) are of wide detection window, high responsivity and high operation temperature. Moreover, QDIPs are less sensitive to the normally incident IR light. In normal case, the normal incident absorption of the devices is 20 % more than conventional QWIPs. This characteristic is advantageous for the fabrication of FPAs due to that no additional light-coupling scheme is required for the device. In theory, QDIPs are of lower dark currents and higher gain than QWIPs, which is advantageous for high-temperature operation of the device.

In recent years, lots of effort has been devoted to the development of quantum-dot infrared photodetectors (QDIPs). The influence of different device parameters on the performance of QDIPs has been investigated. QDIPs with high responsivities and high operation temperatures have been reported by inserting AlGaAs barrier layers in the device structures to depress the dark currents [1-3]. The influence of QD doping density of the devices on the operation voltage and normal incident absorption has been also reported [4]. New device structures with p-type doped GaAs layers inserted within have been proposed to enhance the operation temperature [5-6]. The thermal images taken by a 256 x 256 grating-less QDIP focal-plane array (FPA) operated at 135 K have been also demonstrated [7]. However, considering the thermal imaging applications of QDIPs, two major disadvantages are observed for the devices: (a) for most QDIPs, the detection wavelength is limited in the mid-wavelength infrared (MWIR, 3-5 μm) range and (b) the wafer uniformity of QD samples is worse than the conventional quantum-well infrared photodetectors (QWIPs). To solve this problem, this year we have proposed a new device structure called QD/QW mixed-mode infrared photodetectors (MMIP).

For the first time, we have observed one-photon absorption (MWIR) for the QD structure and two-photon absorption (LWIR) processes for the QW structure within a single device. The device is advantageous for the application of high-temperature multi-color quantum infrared detectors.

Due to that GaAs/AlGaAs QWIPs are of high device performances in the LWIR range (8-12 μm) and most QDIPs operate in the MWIR range (3-5 μm), we would like to include both advantages within one single device structure. In this case, multi-color detections could be achieved by using the device. We have discovered that by embedding InAs QDs within 9 nm GaAs quantum wells, both MWIR and LWIR responses could be observed with $Al_{0.2}Ga_{0.8}As$ barriers and optimized QW doping density. The 10 K spectral responses of the devices are shown in Fig. 1 [8-9]. In the initial attribution, we think that the MWIR response should result from the QD absorption while the LWIR response is from QW absorption. To verify this attribution, responses of the device measured under IR lights with different polarizations are performed. In general, the normal incident absorption of QW structures is expected to be lower than the QD structure [4]. Therefore, if the absorption mechanisms in the two wavelength ranges are different, the normal incident absorption ratio should be different for the two peaks. Our experiments have revealed that lower normal incident absorption is observed for the LWIR response (LWIR : MWIR = 40 : 60). In this case, we could conclude that the MWIR response resulted from QD absorption while the LWIR response is from QW absorption.

According to the previous discussions, we have established a model for the device. A simplified schematic band diagram of the device under positive and negative biases are shown in Fig. 2. We think that when the device is positively biased, most of the photocurrent is composed of the photo-excited electrons via transition processes (a) and (c). When the device is negatively biased, the photocurrent is composed of electrons via transition processes (b) and (d). Among which, transition processes (a) and (b) are of one-photon absorption, while (c) and (d) are of two-photon absorption. The other supporting evidence is the similar energy differences 24.4 and 22.8 meV between (a)-(b) and (c)-(d) transition processes. According to the results, we have successfully combined advantages of QW and QD structures within one single device structure. Besides the MWIR absorption of the QD structure, the high lifetimes of electrons in the QD structure have also made two-photon absorption in the QW structure possible, such that LWIR absorption is also observed. We believe that the structure would be advantageous for the development of high-temperature operation QDIPs. Actually, we have observed both MWIR and LWIR responses of the device at 77 K. The increase of photocurrent with increasing temperatures has been observed for both wavelength ranges, which is quite different from conventional QWIPs. We believe that the unique characteristic would push the device to operate under higher temperatures.

Conclusions

Our research results have revealed that compared with conventional QWIPs, the quantum-dot/quantum-well mixed-mode infrared photodetectors could detect both MWIR and LWIR lights. The increase of photocurrents with increasing temperatures of the device in the both wavelength ranges is different from the invariant photocurrents of conventional QWIPs under different temperatures. We believe that the unique characteristic would push the device to operate under higher temperatures.

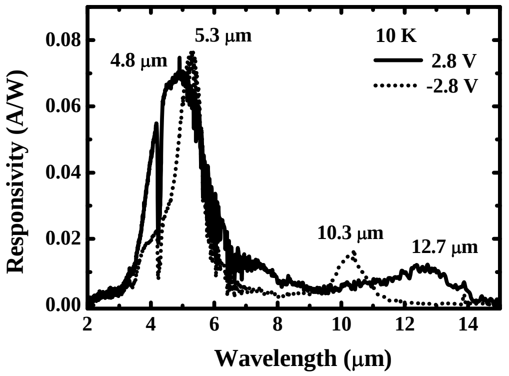

Fig. 1 The 10 K spectral responses of the MMIP at + 2.8 V.

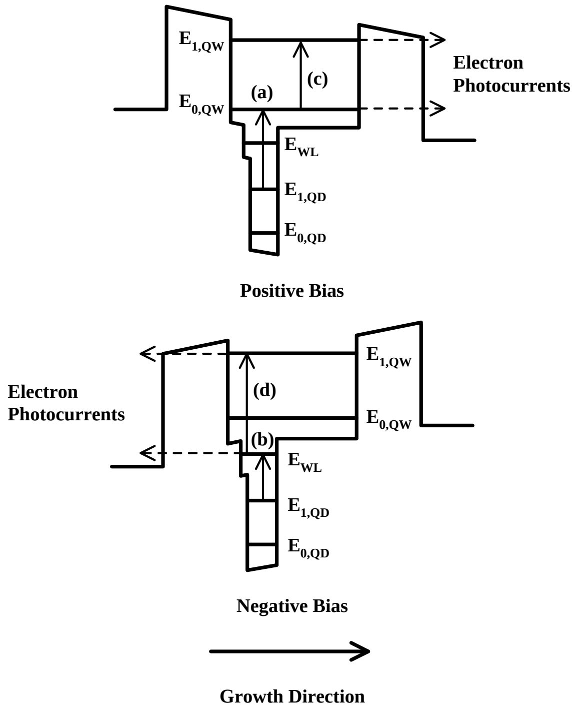

Fig. 2 The schematic band diagrams of the MMIP under positive and negative biases and the transition processes of the electrons.

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