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Optical study of HgCdTe infrared photodetectors using internal photoemission spectroscopy

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We report a study of internal photoemission spectroscopy (IPE) applied to a *n*-type $Hg_{1-x}Cd_xTe/Hg_{1-y}Cd_yTe$ heterojunction. An exponential line-shape of the absorption tail in HgCdTe is identified by IPE fittings of the near-threshold quantum yield spectra. The reduction of quantum yield (at higher photon energy) below the fitting value is explained as a result of carrier-phonon scatterings. In addition, the obtained bias independence of the IPE threshold indicates a negligible electron barrier at the heterojunction interface. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4870479]

The HgCdTe ternary alloy is an ideal material to develop infrared (IR) detectors, owing to its spectral tailorability over the 1–30 μm range, high absorption, and long carrier lifetime.[1,2] Negligible sensitivity of the lattice constant to the variation of cadmium fraction allows for growing various structures based on the same material system, such as *p-n* (Ref. 3) and *n*B*n* (Ref. 4) photodetectors, with the capability of multiple color detection, which is one of the important characteristics in the third-generation IR imaging system.[1] Although long-standing studies on HgCdTe with respect to the characteristics of absorption has been established, detail studies to understand the device physics is still a necessity in order to optimize the device performance. In this Letter, we report an internal photoemission (IPE) study of a $Hg_{1-x}Cd_xTe/Hg_{1-y}Cd_yTe$ heterojunction structure, with a focus on the near-threshold regime of IPE spectra. The IPE threshold related to the band offset of the junction, absorption characteristic of HgCdTe at the band edge, and the effect of carrier-phonon scatterings on the spectral response are discussed.

Photoresponse in the near-threshold regime comes with two features determined by the optical transitions in the active region which create photo-carriers, and the escape of photo-carriers which leads to photocurrents. The escape capability can be mitigated by the loss in the energy or redirection of the carrier as a result of scattering with phonon. The onset of the carrier-phonon scattering depends on the excess kinetic energy of photocarriers.[5] It is expected that this occurs at the above-threshold regime, and after excitation, the excess kinetic energy of carriers should be greater than the phonon energy. Upon scatterings, a portion of photocarriers could remain in the absorber, unable to escape, which leads to degradation in the photoresponse. A detailed study on this should benefit future improvement of the device performance. An approach to study the scattering effects has been recently demonstrated[6] using IPE spectroscopy,[7] through fitting of the near-threshold quantum yield spectra. The quantum yield is defined as the number of escaped photocarriers per photon. This approach was recently applied to the study of type-II InAs/GaSb superlattice photodetectors to determine various band parameters.[6]

A schematic of the $Hg_{1-x}Cd_xTe/Hg_{1-y}Cd_yTe$ sample is shown in Fig. 1(a), consisting of a thin (0.32 μm) top $Hg_{0.68}Cd_{0.32}Te$ layer and a thick (7.33 μm) $Hg_{0.78}Cd_{0.22}Te$ absorber, grown on the Si substrate. Two Ohmic contacts are made to the individual HgCdTe layers. Backside illumination was used for all of the measurements. Figure 1(b) shows the typical quantum yield spectra at 5.3 and 78 K. The undulation is related to the optical interference inside the substrate. The low-energy cut-off is due to the escape of photo-carriers from the absorber (originating from the optical transition schematically shown in the inset). Features associated with the band gap of the $Hg_{0.68}Cd_{0.32}Te$ layer, which should be around 0.28 and 0.29 eV for 5.3 and 78 K,[8] respectively, are not observed. Notice that, unlike most semiconductors, the optical absorption edge of HgCdTe shifts to high energies at elevated temperatures.[8]

The quantum yield,[7] proportional to the multiplication of spectral responsivity and photon energy, was obtained by measuring spectral response. The details of the IPE principle and formalism used to fit yield spectra are described in Refs. 6 and 7. Quantum yield is dominantly determined by the photoexcitation of electrons in the absorber, described by an energy distribution function (ρ), and their escape over the barrier, described by a probability function.[7] The energy distribution is proportional to the joint density of states (JDOS), which can be deduced from the absorption coefficient $[\alpha(h\nu)]$ using the relationship: JDOS $\sim \alpha \times h\nu$. This also means that one can study the absorption property through IPE analysis of the quantum yield spectra.

Previous studies have shown that the assumption of the parabolic-band approximation (PBA), i.e., JDOS $\sim (\epsilon - h\nu)^{1/2}$, is valid for GaAs/AlGaAs heterojunctions[7] and type-II InAs/GaSb superlattice structures.[6] In these studies, dopant-caused band tailing has the negligible effects on the spectral yield. This is in part due to the process where the escape of photocarriers over a potential barrier[7] requires optical transitions ending up at the energy states above the band edge of the barrier. Also, band tailings are insignificant in GaAs and type-II superlattices. For HgCdTe, however, the Urbach tail[9] is known to significantly distort the absorption

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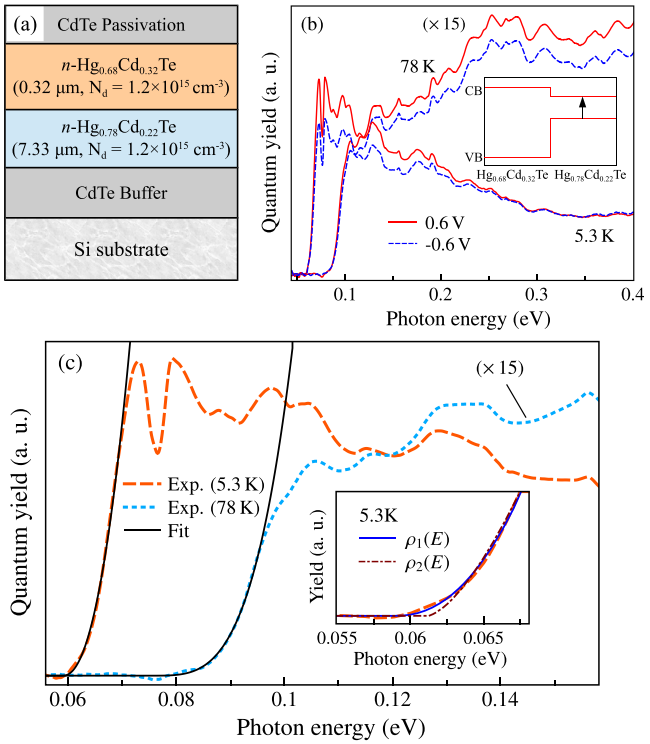

FIG. 1. (a) Schematic of the *n*-type $Hg_{0.78}Cd_{0.22}Te/Hg_{0.68}Cd_{0.32}Te$ heterojunction structure. (b) The quantum yield spectra at 5.3 and 78 K. Spectra measured at positive and negative biases have the similar profile. Inset shows the schematic band alignment (without considering the space charge effect and composition grading at the junction interface) and the dominant optical transition which occurs in $Hg_{0.78}Cd_{0.22}Te$. (c) The quantum yield spectra at 0.6 V, along with IPE fittings (solid line). Inset: Comparison of fittings using different energy distribution functions, where ρ_1 is an exponential function, while ρ_2 represents for PBA approximation.

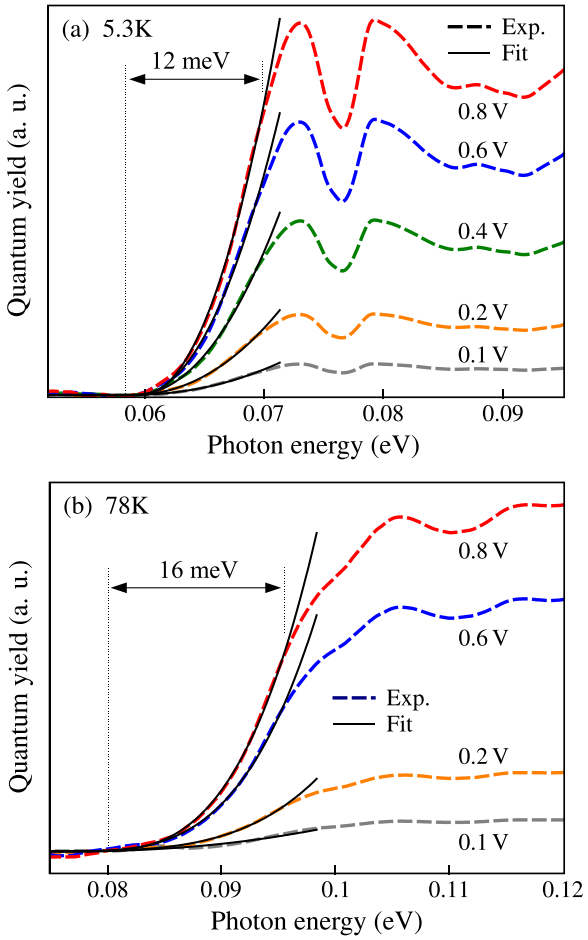

FIG. 2. IPE fittings of the near-threshold quantum yield spectra at (a) 5.3 K and (b) 78 K. The yield drops below the fitting curve at the point about 12–16 meV above the threshold. This value is consistent with the energy of the HgTe-like LO phonon in $Hg_{0.78}Cd_{0.22}Te$.[13]

edge. As shown in the inset of Fig. 1(c), the IPE fitting based on PBA shows good agreement with the experimental curve at the high-energy range, but fails to explain the spectral yield in the near-threshold regime. One possible reason could be due to the trivial influence of the potential barrier on the escape of photocarriers, which means that the spectral yield is mostly determined by the $Hg_{0.78}Cd_{0.22}Te$ absorber. As a consequence, band tailing should be properly considered in order to fit the yield spectra [see the solid line in the inset of Fig. 1(c)].

In terms of the structure shown in Fig. 1(a) and the band alignment shown in the inset of Fig. 1(b), electrons escaping into the $Hg_{0.68}Cd_{0.32}Te$ layer under a positive bias need to overcome a barrier associated with the conduction band offset (CBO) of the $Hg_{0.78}Cd_{0.22}Te/Hg_{0.68}Cd_{0.32}Te$ junction. The IPE threshold of this should be different under negative bias where surmounting the barrier is not needed. However, such a difference cannot be identified from the spectral yield as shown in Fig. 1(b). Both under positive and negative biases display similar spectral profile, and no apparent shifting in the thresholds can be observed.

To understand the bias dependence of the IPE threshold, fittings to the near-threshold yield spectra in order to obtain the threshold energies are carried out, as shown in Fig. 1(c) (different temperatures) and Fig. 2 (different biases). Band tailing means non-zero absorption at the photon energy of E_g (band-gap). Corresponding modifications to the JDOS are needed to include the band tailing effect. An empirical exponential function proposed by Chu *et al.*,[10] i.e., $\alpha \sim \exp[\beta(h\nu - E_g)]$ represents one such modification. As shown in the inset of Fig. 1(c), the fitting using the exponential energy distribution (ρ_1) shows improvement over that using PBA (ρ_2). In addition to this Moazzami *et al.*[11] proposed the form of $\alpha \sim (h\nu - E_g)^n/h\nu$ with the exponent n as a fitting parameter. Although good agreement with the yield spectra can be achieved, the obtained parameter n cannot be consistently interpreted, which must vary for spectra undertaken at different biases. For this reason, formalism of Chu *et al.* is used throughout. Based on fittings to yield spectra at different biases (Fig. 2), the threshold energies as a function of bias are obtained, as shown in Fig. 3(a).

It should be noted that the threshold energies of the $Hg_{0.78}Cd_{0.22}Te/Hg_{0.68}Cd_{0.32}Te$ junction at positive biases should correlate with the optical transitions across the band gap. In order to escape over the $Hg_{0.68}Cd_{0.32}Te$ barrier, the minimum photon energy absorbed should be $E_g + \Delta E_c$, where E_g is the band-gap of $Hg_{0.78}Cd_{0.22}Te$ and ΔE_c is the value of CBO. Adachi[12] suggests $\Delta E_c(x) = 1.21 - 1.21x$ for the $Hg_{1-x}Cd_xTe/CdTe$ heterojunction. The CBO of $Hg_{1-x}Cd_xTe/Hg_{1-y}Cd_yTe$ can therefore be calculated as $\Delta E_c = \Delta E_c(x) - \Delta E_c(y)$. The expected ΔE_c amounts to 0.121 eV. The threshold of electrons overcoming a potential

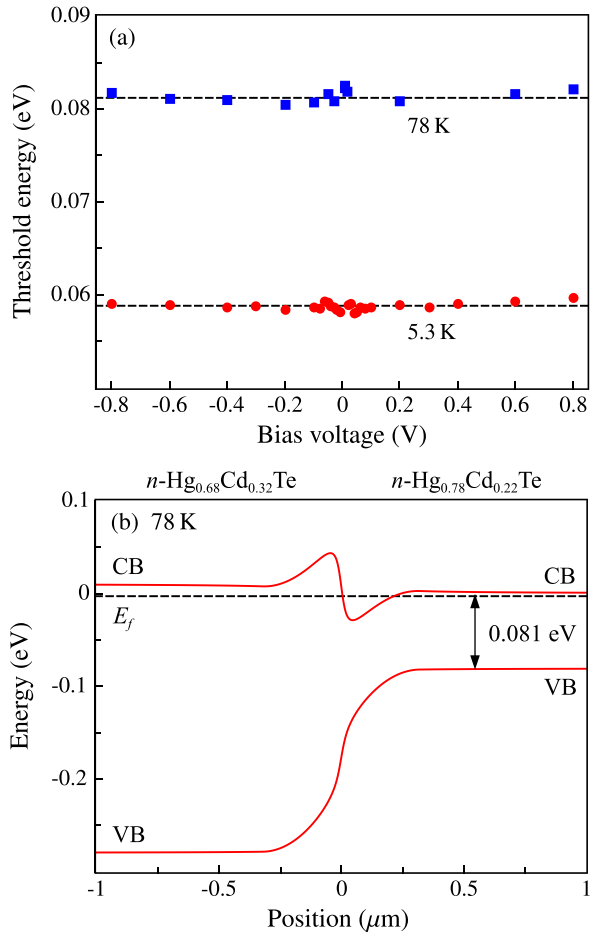

FIG. 3. (a) Obtained threshold energies as a function of bias at 5.3 K and 78 K. (b) A schematic band diagram of the *n*-type $Hg_{0.68}Cd_{0.32}Te$/$Hg_{0.78}Cd_{0.22}Te$ heterojunction based on IPE analysis.

barrier is typically subject to bias-caused lowering effect due to the image force effect.[7] However, such a behavior is not observed in this study, as shown in Fig. 3(a). Also, the obtained threshold agrees with the band gap of $Hg_{0.78}Cd_{0.22}Te$, according to formalism of Laurenti *et al.* band-gap.[8] This leads us to conclude that no potential barrier exists at the heterojunction. Figure 3(b) shows a schematic band diagram, without any appreciable effects of the junction interface on the transport of the electrons. One of the reasons causing this is that the band spike associated with the band offset is smoothed out by the composition grading at the interface. Since the Fermi levels in two HgCdTe regions should be aligned and also as a result of the unintentional composition grading at the heterointerface, the band-offset spike is greatly reduced. The highest conduction barrier height is determined by the width of the interface gradient region. From the growth point of view, the interface barrier can be controlled as desired, for example, by intentionally growing an interface composition grading layer. Reducing the barrier height gives rise to a higher collection efficiency of photo-electrons. The same effect can be obtained for the valence band when the materials are *p*-type doped. As a result of the aligned Fermi levels between the two MCT layers, the difference of energies between their CBs is nearly zero.

One might notice that the quantum yield shows a drop at the photon energy above the threshold, as shown in Fig. 2. The deviation point is about 12–16 meV, higher than the threshold for the temperatures between 5.3 and 78 K. For the photons with the energy higher than this value, the rate of the further yield increase appears to be much reduced, which suggests a reduced IPE probability. The energy point, at which the IPE yield decrease is observed, is independent of the bias. It is understandable that scatterings with the longitudinal-optical (LO) phonons are expected to occur when the kinetic energies of carriers are greater than the energy of LO phonon. This leads to the relaxation of the photocarriers and a reduction of their energies. One of the consequences is the inability of photocarriers escaping over the barrier, thus causing a reduction in the escape probability. This scattering effect is confirmed by identifying the energy difference between the deviation point (between the fitting and experimental spectra) and the threshold energy, which is nearly the same as that of the HgTe-like LO, i.e., 17 meV at 77 K.[13]

To conclude, IPE studies on the HgCdTe photodetectors are reported. IPE analysis shows that the exponential absorption tail, which affects the energy states above the band gap gives good fittings of experimental spectra. Carrier-phonon scatterings are confirmed by observing a drop of the quantum yield below the IPE fitting value. The dropping point is nearly the energy of the HgTe-like LO phonon above the threshold. IPE fittings also confirm the negligible electron barrier at the *n*-type $Hg_{0.68}Cd_{0.32}Te$ (0.32 μm)/$Hg_{0.78}Cd_{0.22}Te$ (7.33 μm) heterojunction interface.

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