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Proceedings Paper:

Perera, AGU, Lao, YF, Li, LH et al. (2 more authors) (2015) Tunable hot-carrier photodetector. In: 2015 IEEE Summer Topicals Meeting Series (SUM). 2015 IEEE Summer Topicals Meeting Series (SUM), 13-15 Jul 2015, Nassau, Bahamas. IEEE , pp. 61-62. ISBN 9781479974689

https://doi.org/10.1109/PHOSST.2015.7248193

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Tunable hot-carrier photodetector

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***Abstract* – The wavelength limit (λ_c) of detection in a conventional photodetector is determined by the activation energy of the semiconductor structure through the relationship: $\lambda_c = hc/\Delta$, where Δ also determines the detector noise (dark current) and hence its performance such as the operating temperature. A long wavelength photodetection principle has been demonstrated by using a hot-cold carrier energy transfer mechanism. A detector with Δ = 0.32 eV experimentally shows response up to 55 µm. The extend response is tunable by varying the degree of hot-hole injection.**

I. INTRODUCTION

The hot-carrier dynamics is the subject of many studies in semiconductor physics and devices. [1] Inelastic scattering of carriers with lattice is a major channel to relax hot carriers, in which energy dissipates as heat. In this work, we demonstrate a carrier-carrier interaction induced energy transfer mechanism [2] which enables extension of the spectral threshold wavelength into the very-long wavelength infrared (VLWIR) range. A *p*-type GaAs/AlGaAs heterojunction photodetector with Δ = 0.32 eV experimentally shows a response up to 55 µm, whereas without the hot-carrier effect the threshold should correspond to ~3.9 µm according to relationship: $\lambda_c = hc/\Delta$. The advantage of the hot-carrier mechanism is a new detection concept which separates the photoemission threshold from affecting the spectral response, allowing minimizing the detector noise by using a high activation energy.

II. DEVICE STRUCTURE

The structure of demonstrated photodetectors based on internal photoemission (IPE) is shown Fig. 1 (a). The typical photodetection includes photoexcitation of carriers in the absorber (i.e., emitter) and their escape over the barrier by the IPE process occurring at the emitter-barrier interface. The detector structure consists of three *p*-type doped (1×10^{19} cm^{-3}) GaAs regions, i.e., injector, absorber and collector, respectively. The valence-band (VB) alignment is illustrated in Fig. 1 (b). The *p*-type doping provides free holes which are responsible for photon absorption through intra- and inter-valence band transitions. [3]

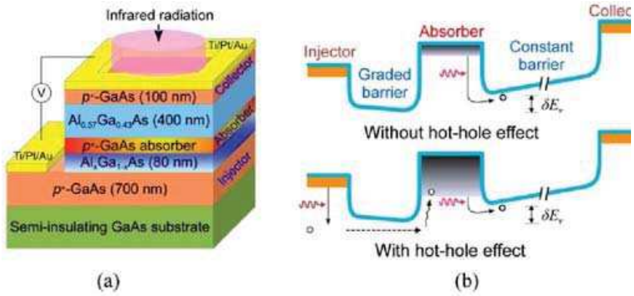

Figure 1: (a) Schematic of the *p*-type GaAs/$Al_xGa_{1-x}As$ hot-hole photodetector structure. (b) Schematic valence-band diagrams (including band bending) under negative bias (positive polarity applied on the injector), with a comparison of hole photoexcitation and emission without (top) and with (bottom) hot-cold hole energy transfer. δE_v is the offset between the barriers below and above the *p*-GaAs absorber.

A reverse bias (positive polarity on the injector) is applied to the sample to drive photoexcited hot holes moving from the injector toward the collector. When they pass through the absorber region, scattering with cold holes could occur, which cools the hot holes by giving their excess energies in part to cold holes and to the lattice. One of the consequences is a change in the energy distribution of cold holes towards the higher energy states. [4]

III. RESULTS AND DISCUSSION

The spectral response of the detector (with an 80 nm-thick absorber) at 5.3 K is shown in Fig. 2. A response beyond the wavelength limit of detection determined by $\lambda_c = hc/\Delta$ (3.9 µm) has been measured. This clearly shows a photoresponse signal in the long-wavelength range (> 3.9 µm). In general the observed VLWIR response could be due to a bolometric effect, or an impurity-band/free-hole carrier based response. The absorber, though, has a major effect on the bolometric response and impurity-band absorption. By measuring a control sample which contains the same GaAs absorber, we can exclude these two mechanisms as a cause of the VLWIR response. Additionally, the bolometric response, proportional to the temperature variation of the absorber upon photon absorption and the corresponding resistance change, monotonically increases with increasing bias. This effect contrasts with the strongly bias-dependent VLWIR response.

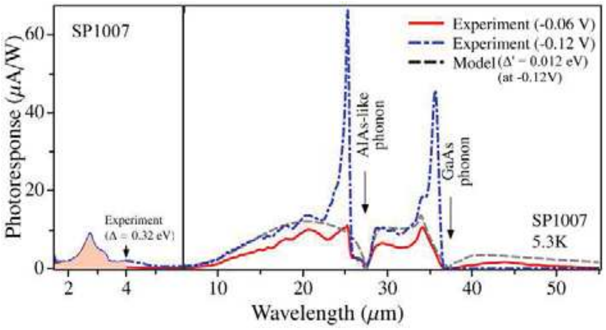

Figure 2: Experimental photoresponse at 5.3 K, and the escape-cone model (dashed line) fit, with reduced threshold energy (Δ') as 0.012 eV (103 µm in wavelength). The marked arrows are associated with GaAs and AlAs-like phonons. Inset: Differential SWpump versus bias, showing distribution peaks (i, ii and iii).

Since the escape-cone model predicts the spectral response reasonably well, [5] it was used to the predict the long-wavelength threshold. As shown in Fig. 2, the observed VLWIR response agrees well with a fitting value $\Delta = 0.012$ eV, although the design and Arrhenius plot gives $\Delta = 0.32$ eV. The model also well explains features associated with GaAs and AlAs-like phonons

The occurrence of the VLWIR response due to the hot-cold carrier interaction means that one can tune the degree of hot-hole injection to control this response as shown in Fig. 3. In this measurement, a long-pass filter with λ_{CO} =4.5 µm (cut-off wavelength) is used to prevent the creation of hot holes by the high-energy photons from the spectrometer. Instead, the generation of hot holes is enabled by sending an external high-energy light (P_{ext}). The photocurrent, represented by the spectral weight of the response, at different excitation levels is shown in Fig. 3 (a). Fig. 3 (b) shows the excitation power spectra. The variation of the VLWIR response (at -0.1 V) with the excitation power is plotted in Figs. 3 (c), indicating that the VLWIR response is enabled by increasing the excitation intensity, demonstrating the response tunability varying the degree of hot-hole injection.

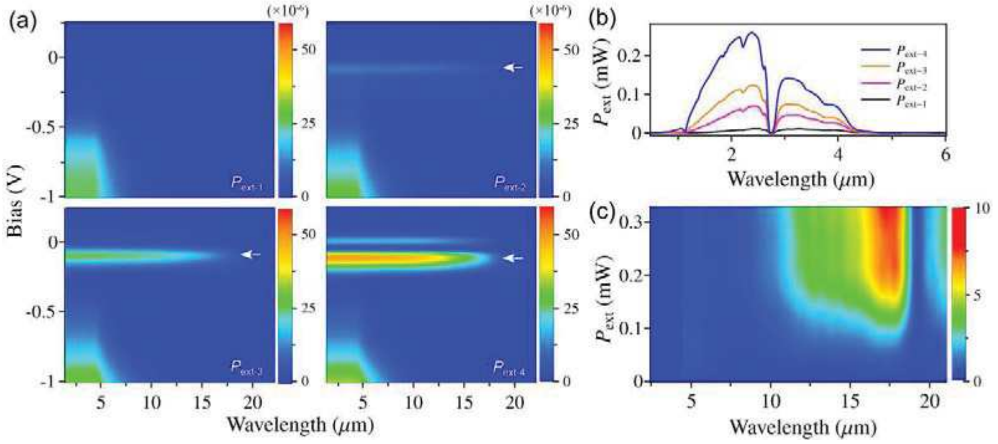

Figure 3 (a) Spectral weights of response obtained using different intensities of optical excitation source. The left image in the first panel was obtained using P_{ext-1}, which is very similar to the case where the external optical source is fully blocked. (b) Power spectra of the excitation optical source (incident on the sample with an active area of $260 \times 260\ \mu m^2$). A quartz glass filter is used to enable spectra up to 4.8 µm which ensures the excitation optical source is only used to excite hot holes. (c) The dependence of the VLWIR response (at -0.1 V) on the excitation power.

I. CONCLUSIONS

To conclude, we have demonstrated an internal photoemssion detector with response up to 55 µm, which is tunable by varying the degree of hot-hole injection. This study shows the possibility of incorporating long-wavelength response in a short-wavelength detector.

ACKNOWLEDGMENT

This work was supported in part by the US Army Research Office (grant no. W911NF-15-1-0018), monitored by William W. Clark, and in part by the US National Science Foundation (grant no. ECCS-1232184, monitored by Mahmoud Fallahi).

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