Tunnel Field-Effect Transistor Heterojunction Band Offsets by Electron and Hole Internal Photoemission

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The electrical performance of a tunnel field effect transistor (TFET) depends critically on the band offset at their semiconductor heterojunction. Historically it has been rather difficult to experimentally determine how the electronic band is aligned at the interface. We report an experimentally unique method to ascertain a complete energy band alignment of a broken-gap tunnel field-effect transistor InAs/GaSb hetero-junction. By using graphene as an optically and electrically transparent electrode in a traditional internal photoemission (IPE), both the electron and hole barrier heights at the InAs/GaSb interface can be measured. Conventional IPE on TFET structure has been recently reported on InAs/p^+AlGaSb heterojunction.[1] In this talk, a more elaborate approach will be presented which simultaneously resolves both valence and conduction band offsets at the heterojunction interface without the required layer configuration used in Reference 1. Specifically, the offsets of the valence bands are determined by *electron* photoemission whereas those of conduction bands are measured by the *hole* photoemission. This method was possible by using graphene as a semitransparent electrode in the IPE setup.[2]

Figure 1 illustrates the schematic of a TFET InAs/GaSb heterojunction used in the IPE measurement where a bias V_g applied across the structure and the photocurrents are measured as a function of photon energy of incident light. The IPE quantum yield is defined as the ratio of photocurrent and incident photon. Shown in Figs. 2(a) and 2(c) are the cube roots of IPE quantum yield, $Y^{1/3}$, versus photon energy when$V_g > V_{FB}$ where V_{FB} is the flatbandvoltage for the heterojunction with a 29 nm and 10 nm InAs layer, respectively. We can confirm from which semiconductor of the heterojunction the photocurrents come by observing whether the photoemission yield contains specific optical critical point (CP) belonging to that material. The CP's of InAs and GaSb are recognized from their dielectric functions shown in Fig. 2b. In Fig. 2(a), the $Y^{1/3}$ plot for 29 nm InAs sample contains only E_0' (~ 4.4 eV) and E_2 (~ 4.6 eV) CP, of InAs. None of GaSb CP's appears in the photoemission spectrum since the incidence light is mostly absorbed in the 29 nm InAs layer.[1] Therefore, the photocurrents originate from InAs layer alone. While in Fig. 2(c), the $Y^{1/3}$ plot for much thinner (10 nm) InAs layer, which allows more light transmitted to the GaSb layer, contains two CP's, E_0' and $E_0' + \Delta_0'$, of GaSb, which confirm that the photocurrents come from GaAs substrate. From these observations, we can conclude that the thresholds in Fig. 2(a) are the barrier heights from the InAs (n-type TFET) valence band maxima to the Al_2O_3 conduction band minimum and the thresholds in Fig. 2(c) are the barrier heights from the GaSb valence band maxima to the Al_2O_3 conduction band minimum. The zero-field electron barrier heights from the InAs (n-type TFET) valence band maxima to the Al_2O_3 conduction band minimum and from the GaSb (p-type TFET) valence band maxima to the Al_2O_3 conduction band minimum are determined (from the field dependence, not shown) to be 3.42 eV and 2.94 eV, respectively.

In traditional IPE measurements, the hole photocurrent (if present) from semiconductor is negligible compared to the electron photocurrent from the semi-transparent gate (usually thin metal) due to the much lower quantum yield for hole emission. Rusen *et al.* first reported using graphene as transparent electrode to measure the hole photoemission in an IPE measurement.[2] Similar hole photoemission processes are observed for InAs-GaSb heterojunction. Shown in Fig. 3 is the $Y^{1/3}$ of the hole emission from InAs conduction band to the Al_2O_3valence band as a function of photon energy at various biases. Since the 29 nm thick InAs layer absorbs about 60% of the incident light, the photoemission from the InAs layer is observed (Fig. 2(a), Fig. 3). The field-independent barrier height measured from InAs conduction band minimum to the Al_2O_3 valence band maximum is determined to be 3.20 eV from Fig. 3. While for the thin InAs layer InAs-GaSb heterojunction sample, hole emissions from InAs and GaSb layer are also observed (not shown), and the barrier height from GaSb conduction band minimum to the Al_2O_3 valence band maximum is determined to be 4.10 eV.

The complete band diagram of the thick and thin InAs layer InAs-GaSb broken-gap hetero-junction can now be constructed from and shown Fig. 4(a) and (b). A band gap of 6.27 eV can be calculated from the measured barrier heights and found to be consistent with the band gap of 6.30 eV extracted from the Al_2O_3optical absorption. In conclusion, we have demonstrated that the use of graphene as transparent electrode in IPE measurement can quantitatively characterize both the electron and hole barrier heights in heterojunction TFETs.

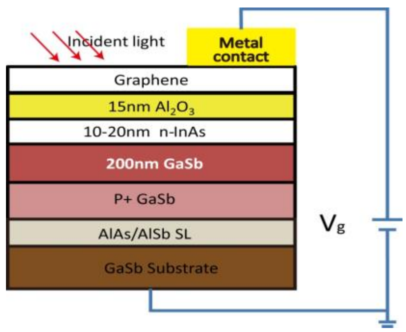

Fig1. Schematic of the IPE measurement of the graphene/Al_2O_3/InAs/GaSb heterojunction

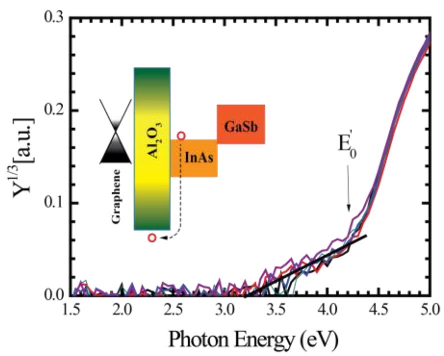

Fig. 3 $Y^{1/3}$ of hole photoemission hole emission from InAsas a function of photon

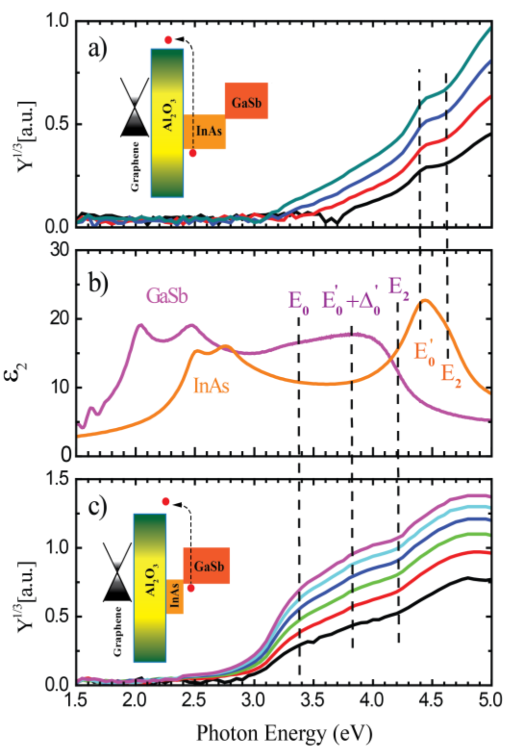

Fig. 2 Cube root of the IPE yield ($Y^{1/3}$) as a function of photon energy for different gate bias. Thick (a) and thin (c) InAs layer broken gap TFET electron emission $Y^{1/3}$. (b) The pseudodielectric function of InAs (red) and GaSb (black), measured by spectroscopic ellipsometry

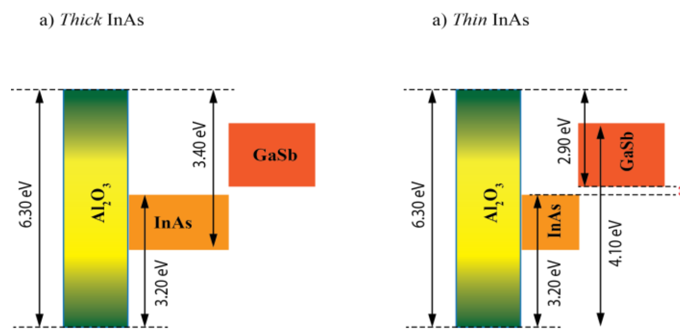

Fig. 4 The determined band diagram of the broken gap TFET heterojunction

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