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Band offsets at the (1 0 0)GaSb/Al_2O_3 interface from internal electron photoemission study

V.V. Afanas'ev [a,*], H.-Y. Chou [a], A. Stesmans [a], C. Merckling [b], X. Sun [b,c,d]

[a] Department of Physics and Astronomy, University of Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium
[b] IMEC, Kapeldreef 75, B-3001 Leuven, Belgium
[c] Department of Electrical Engineering, University of Leuven, Kasteelpark Arenberg 10, B-3001 Leuven, Belgium
[d] Department of Electrical Engineering, Yale University, New Haven, CT 06520, USA

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ABSTRACT

From electron internal photoemission and photoconductivity measurements at the (1 0 0)GaSb/Al_2O_3 interface, the top of the GaSb valence band is found to be 3.05 ± 0.10 eV below the bottom of the Al_2O_3 conduction band. This interface band alignment corresponds to conduction and valence band offsets of 2.3 ± 0.10 eV and 3.05 ± 0.15 eV, respectively, indicating that the valence band in GaSb lies energetically well above the valence band of $In_xGa_{1-x}As$ ($0 \leqslant x \leqslant 0.53$) or InP.

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1. Introduction

Quantum well (QW) channel structures are seen as a promising way to incorporate $A_{III}B_V$ semiconductors in metal–oxide-semiconductor (MOS) devices without impairing the III–V intrinsically high bulk mobility. However, in the case of p-channels, the QW concept faces a problem associated with the weak sensitivity of the valence band (VB) energy to the cation (Ga or In) composition of $In_xGa_{1-x}As$ [1,2], which is considered as the best material for the n-channel structures. In the present work, addressing the possibility of VB edge tuning by replacing As with Sb, we determined the electron energy band offsets at the (1 0 0)GaSb/Al_2O_3 interface by combining electron internal photoemission (IPE) and photoconductivity (PC) measurements.

The top of the GaSb VB is found to be at 3.05 ± 0.10 eV below the oxide conduction band (CB). This band alignment corresponds to CB and VB offsets of 2.3 ± 0.10 eV and 3.05 ± 0.15 eV, respectively. As compared to the interfaces of GaAs, $In_xGa_{1-x}As$ ($x \leqslant 0.53$), and InP with Al_2O_3, the top of the GaSb valence band is energetically located well above the VB of the indicated semiconductors, suggesting the feasibility of using GaSb in QW p-channel structures. In addition, we found that the photoelectron escape depth from GaSb in the IPE experiment is large enough ($\lambda_e \approx 4$ nm) to allow probing of the band edges in QW channels at a depth of several nanometers from the interface.

2. Experimental

The formation of a narrow-gap interlayer (IL) caused by oxidation of GaSb during oxide deposition poses an experimental challenge because the IL may lead to interface barrier lowering, thus impairing extraction of fundamental band offsets. To avoid this problem, the oxidant supply to the GaSb surface was limited by using the molecular beam epitaxy (MBE) technique to deposit amorphous Al_2O_3 on (1 0 0)GaSb layers epitaxially grown on (1 0 0)InP substrates. Evaporation of Al in an atomic oxygen ambient under an overall pressure of 3×10^{-6} torr was used to grow a 10-nm thick alumina layer with the substrate kept at 50 °C [3]. Neither cross-sectional transmission electron microscopy nor X-ray photoelectron spectroscopy could reveal a Ga oxide between GaSb and Al_2O_3, indicating insignificant oxidation of GaSb.

MOS capacitors of 0.5 mm^2 area were fabricated by thermoresistive evaporation of semitransparent 13–15-nm thick Au or Al electrodes. These structures were used for IPE and PC measurements carried out at room temperature in the photon energy ($h\nu$) range 2.0–6.8 eV. The quantum yield (Y) was determined by normalizing the measured photocurrent to the incident photon flux [4]. The yield spectral dependences were analyzed to determine the energy thresholds of electron transitions delivering free charge carriers to the insulating oxide.

3. Results and discussion

Yield spectral curves are shown in Fig. 1a for the heavily-doped p-type (Si-doped: $n_a = 3 \times 10^{18}$ cm^{-3}) (1 0 0)GaSb/Al_2O_3/Au sample. When measured under positive bias the spectra show

* Corresponding author. Tel.: +32 0 16 327167; fax: +32 0 16 327987.
E-mail address: valeri.afanasiev@fys.kuleuven.be (V.V. Afanas'ev).

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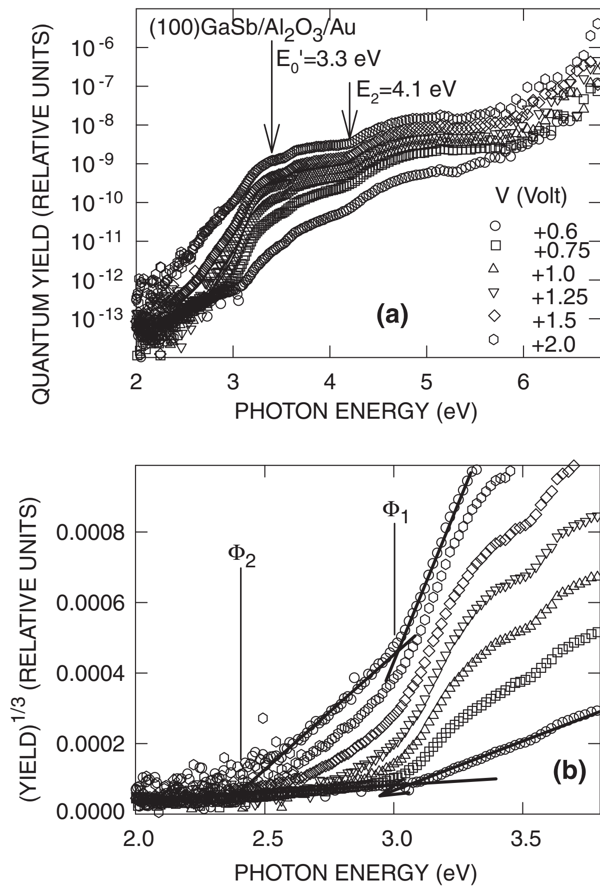

Fig. 1. (a) Logarithmic plot of the quantum yield as a function of photon energy as measured on a p-type (1 0 0)GaSb/Al_2O_3 (10 nm)/Au (13 nm) sample under different voltage (V) values applied to the metal electrode. Arrows mark the energies of direct optical transitions in the GaSb crystal. (b) Determination of the spectral thresholds Φ_1 and Φ_2 of electron IPE from GaSb into Al_2O_3 using the $Y^{1/3}$–$h\nu$ plots. With respect to the applied voltage, symbols have the same meaning as indicated in panel (a). Lines guide the eye; vertical lines mark the thresholds.

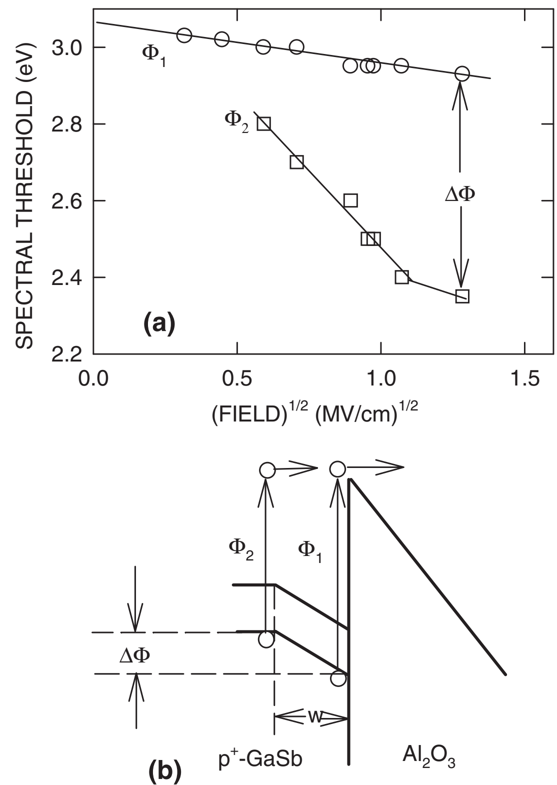

Fig. 2. (a) Schottky plot of the inferred spectral thresholds of electron IPE from the VB of GaSb into the CB of Al_2O_3. (b) Schematic of the observed electron transitions, one with spectral threshold corresponding to excitation of electrons at the surface of GaSb (Φ_1) and the other with spectral threshold corresponding to excitation from behind its space-charge layer of thickness (Φ_2), where the latter causes a threshold lowering by $\Delta\Phi$.

field-independent features at $E_0' = 3.3$ eV and $E_2 = 4.1$ eV, coinciding in energy with direct optical transitions between high-symmetry points in the Brillouin zone of GaSb, i.e., $\Gamma_8^V \rightarrow \Gamma_7^C$ and $X_5^V \rightarrow X_3^C$, respectively [5]. This observation indicates that the photocurrent observed is due to electron IPE from the VB of GaSb into the alumina CB. Irrespective of the metal electrode used, at $h\nu > 6$ eV the photocurrent spectra measured for both orientations of the electric field in the oxide (not shown) reveal the onset of intrinsic PC of the oxide layer with a spectral threshold $E_g(Al_2O_3) = 6.1 \pm 0.1$ eV as determined from $Y^{1/2}$–$h\nu$ plots. This value is in good agreement with the results for amorphous (a-) Al_2O_3 layers grown by a variety of techniques on Si or other semiconductors [4,6]. The PC spectra also reveal a weak photocurrent with spectral threshold close to the bandgap width $E_g(Ga_2O_3) = 4$ eV of MBE-grown Ga_2O_3 [7], with the quantum yield being roughly two orders of magnitude below that of the Al_2O_3 PC. This yield ratio allows us to roughly estimate the maximum amount of Ga oxide present as being about or less than 1% of the Al oxide film, i.e., below one monolayer.

The spectral thresholds of electron IPE from GaSb were found using $Y^{1/3}$–$h\nu$ plots [8], as illustrated in Fig. 1b. The curves measured under low positive bias allow one to determine the onset energy Φ_1 of electron IPE from the GaSb into the oxide. With increasing oxide field a lower threshold Φ_2 becomes also visible. To determine the *intrinsic* zero-field interface energy barriers, the spectral thresholds were plotted as a function of the square root of the average electric field in the oxide (the Schottky plot) [4]. The results, shown in Fig. 2a, indicate that the threshold Φ_1 depends weakly on the field, which would be consistent with direct IPE of electrons from GaSb into the CB of Al_2O_3. The zero-field barrier height of $\Phi_1 = 3.05 \pm 0.10$ eV corresponds to the energy difference between the GaSb VB top and the Al_2O_3 CB bottom. Using a 0.73 eV gap width for GaSb and the 6.1-eV gap of alumina found from the PC spectra, the CB and VB offsets at the (1 0 0)GaSb/Al_2O_3 interface are obtained as 2.3 ± 0.10 eV and 3.05 ± 0.15 eV, respectively.

The Φ_2 threshold lowering with increasing strength of the electric field it is likely caused by the field [cf. Fig. 1b] penetration in the p^+-type GaSb photoemitter: the field induces band bending in GaSb at a depth comparable to the photoelectron mean free path. As shown in Fig. 2b, electrons excited deep in the GaSb will acquire additional energy associated with the band bending in the narrow space-charge layer of the semiconductor. This means that their IPE into the Al_2O_3 CB becomes possible at lower photon energy than IPE from electron states at the surface of GaSb. The threshold lowering of about 0.6 eV, denoted as $\Delta\Phi$ in Fig. 2, suggests that it is possible for electrons photoexcited at the edge of the depletion layer in GaSb at the depth w to reach the interface with Al_2O_3 and contribute to IPE. The width of the depletion layer corresponding to the band bending of 0.6 eV can be calculated from the known acceptor concentration and GaSb parameters, as being about $w = 20$ nm. As the quantum yield of electron IPE from the GaSb bulk is approximately 100 times lower that in the case of surface excitation (see the curve corresponding to +2 V bias in Fig. 1a), we estimated the mean photoelectron escape depth from GaSb to be about $\lambda_e \approx 4$ nm. This value significantly exceeds the

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