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Measurement of isotype heterojunction barriers by C-V profiling a)

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The Debye length smearing that occurs in C-V profiling has precluded the use of C-V profiling from an adjacent Schottky barrier to measure the magnitude of energy band discontinuities at barriers in isotype heterojunctions. It is observed, however, that in such a process both the number of the charge carriers and the moment of their distribution are conserved. This information permits the extraction of values for both the conduction band discontinuity $\Delta E_c$ and any interface charge density. This technique and experimental results for an LPE-grown $n$-$N$ GaAs-$Al_{0.3}Ga_{0.7}$ As heterojunctions are described. We find $\Delta E_c = 0.248$ eV, corresponding to about to $0.66\Delta E_g$ rather than Dingle’s commonly accepted value $0.85\Delta E_g$. The difference is attributed to compositional grading during LPE growth.

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In this letter we describe a simple and potentially powerful method to measure the conduction band discontinuity $\Delta E_c$ of only weakly rectifying $n$-$N$ (or $p$-$P$) heterojunctions (HJ) by a novel application of C-V profiling through a HJ, from a Schottky Barrier (SB) adjacent and parallel to the HJ, as shown in Fig. 1 (a). It is well known that it is possible, by C-V profiling, to determine the spatial distribution of the free electrons in a nonuniform semiconductor. In conventional C-V profiling, this information is used to determine the doping distribution. We assume instead that the doping distribution is uniform on both sides of the HJ, and extract band structure information.

If the electron distribution obtained by C-V profiling were exact, one could determine the conduction band edge $E_c(x)$ from the familiar relation

$$E_c(x) - E_F = -kT \ln \left[ n(x)/N_c(x) \right], \quad (1)$$

assuming nondegeneracy. The HJ conduction band discontinuity $\Delta E_c$ as well as any interface charges could then be determined from $E_c(x)$ and its slope. However, the resolution of C-V profiling is limited by the Debye length. If the semiconductor contains a HJ with a large conduction band discontinuity, there will be a depletion region on one of the two sides of the HJ, inside which the Debye length is very large, usually much larger than the total width of this region, usually much larger than the total width of this region. The measured apparent carrier concentration $n(x)$ is then not at all the true local carrier concentration $n(x)$, and $E_c(x)$ obtained from (1) is not the true conduction band edge distribution: the band structure appears as if the HJ were heavily graded.

This point is illustrated in more detail in Fig. 1. We assume that the SB is on the side with the lower conduction band, and we consider that particular value of reverse bias $V$ for which the carrier concentration at the bottom of the notch is just equal to the bulk carrier concentration on the side with the higher conduction band. If now the applied voltage is increased by $\Delta V$, a distribution $\Delta n(x)$ of electrons will be depleted both from the notch and from the edge of the depletion layer on the other side of the HJ barrier. The total effect is the same as if all electrons had been depleted from the position $\bar{x}$,

$$\bar{x} = \left[ \int_0^\infty \Delta n(x) x \, dx \right] / \left[ \int_0^\infty \Delta n(x) \, dx \right]. \quad (2)$$

If this average position of $\Delta n(x)$ is located inside the HJ barrier region, the electron distribution appears to have a large concentration at $x = \bar{x}$, which could be several orders of magnitude larger than the true concentration $n(\bar{x})$.

A numerically calculated example is shown in Fig. 2 to demonstrate this effect. We consider an abrupt HJ with donor concentrations of $5 \times 10^{15}$ cm$^{-3}$ on both sides, and a conduction band discontinuity $\Delta E_c = 0.317$ eV. (This value corresponds to a GaAs-$Al_{0.3}Ga_{0.7}$ As HJ.) As shown in Fig. 2, this Debye length smearing depends on whether the SB is

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FIG. 1. (a) Shift in conduction band edge at a Schottky-barrier-heterojunction combination, as shown in the inset, under the influence of a voltage increment $\Delta V$. (b) Distribution $\Delta n(x)$ of the carrier concentration depleted by $\Delta V$. 

on the low-\(E_c\) side or on the high-\(E_c\) side. Note that the peak of the carrier concentration for a SB on the low-\(E_c\) side is very close to the interface position \(x_i\).

Although the apparent profile is greatly distorted, one can show that the total number of carriers is conserved in the process: If \(n(x)\) is the real carrier concentration and \(\tilde{n}(x)\) is the measured apparent carrier concentration, then

\[
\int_0^\infty n(x) \, dx = \int_0^\infty \tilde{n}(x) \, dx .
\]

Electrical neutrality requires that this integral be equal to the integral of the (net) donor concentration, plus the density \(\sigma_d\) of any fixed interface charges that might be present. This neutrality may be expressed as a condition for \(\sigma_d\),

\[
\sigma_d = - \int_0^\infty [N_d(x) - \tilde{n}(x)] \, dx .
\]

If \(N_d(x)\) is independently known, a measurement of \(\tilde{n}(x)\) therefore permits an extraction of the interface charge density.

It can further be shown that the moment of the carriers is also conserved in the smearing process

\[
\int_0^\infty n(x) x \, dx = \int_0^\infty \tilde{n}(x) x \, dx .
\]

Consider now the quantity

\[
\Delta \Phi = \frac{\mathcal{E}}{\varepsilon} \int_0^\infty [N_d(x) - \tilde{n}(x)] (x - x_i) \, dx ,
\]

which is simply the electrostatic potential difference \(\Phi(\infty) - \Phi(0)\) between the two sides of the HJ. For a homojunction, \(\Phi(\infty) - \Phi(0)\) is the conventional diffusion potential.

For an abrupt HJ with the conduction band discontinuity \(\Delta E_c\),

\[
\Delta \Phi = \frac{kT}{q} \ln \left[ \frac{n(\infty)/N_c(\infty)}{n(0)/N_c(0)} \right] + \frac{\Delta E_c}{q} .
\]

If \(\tilde{n}(x)\) is measured and \(N_d(x)\) is independently known, the combination of Eqs. (6) and (7) permits the determination of the conduction band discontinuity \(\Delta E_c\).

For many HJ's, \(N_d(x)\) will not be known to sufficient accuracy to permit this procedure. But if the doping profile is known to be uniform on both sides and to change abruptly at the interface, then \(N_d = n \neq n_i\) far away form the junction and the method is applicable. The values of \(N_c\) are presumably known and the only uncertainty is the assignment of \(x\), which, experience shows, is readily guessed quite accurately from the \(\tilde{n}(x)\) profile, using Fig. 2 as a guide.

We present here data for a GaAs-Al\(_{0.3}\)Ga\(_{0.7}\)As heterojunction. The solid curve (---) is the measured apparent \(\tilde{n}(x)\), the broken line (----) is the assumed donor concentration \(N_d(x)\), the dotted curve (.....) is the reconstructed \(\tilde{n}(x)\) assuming a conduction band discontinuity \(\Delta E_c = 0.248\) eV, and an interface charge density \(\sigma_i = 2.7 \times 10^{10}\) cm\(^{-2}\).

![FIG. 2. Apparent electron concentration as seen by C-V profiling through an abrupt heterojunction with a uniform donor concentration \(N_D = 5 \times 10^{19}\) cm\(^{-3}\) on both sides, and with a conduction band discontinuity \(\Delta E_c = 0.317\) eV. This \(\Delta E_c\) corresponds to 0.85\(E_g\) for Al\(_{0.3}\)Ga\(_{0.7}\)As at room temperature. The solid curve (---) is the true electron distribution \(n(x)\), the dotted curve (-----) is the apparent \(\tilde{n}(x)\) for a Schottky barrier on the low-\(E_c\) side, the broken line curve (----) is the apparent \(\tilde{n}(x)\) for a Schottky barrier on the high-\(E_c\) side.](image)

![FIG. 3. Experimental and reconstructed apparent carrier concentration \(\tilde{n}(x)\) for a LPE \(n\)-GaAs-Al\(_{0.3}\)Ga\(_{0.7}\)As heterojunction. The solid curve (---) is the measured apparent \(\tilde{n}(x)\), the broken line (----) is the assumed donor concentration \(N_d(x)\), the dotted curve (.....) is the reconstructed \(\tilde{n}(x)\) assuming a conduction band discontinuity \(\Delta E_c = 0.248\) eV, and an interface charge density \(\sigma_i = 2.7 \times 10^{10}\) cm\(^{-2}\).](image)
measured profiles is quite good. The residual discrepancies are most likely due to grading effects. Although a few other HJ's showed similarly good fits, for the majority of the devices from the same wafer the discrepancies were about twice as large. On other wafers the discrepancies were larger.

The interface charge density found here is much smaller than the value assumed by Kroemer et al.2 to explain the high photocollection efficiencies of p-N HJ's and the absence of rectification for n-N HJ's. Devices with such low interface charge should rectify, and we have found that the present HJ's do indeed rectify weakly. The degree of rectification is about what one would expect from the doping and the band structure. The details will be presented elsewhere in a different context.

The conduction band discontinuity found is about 0.07 eV less than the value assumed by Dingle's rule.1 Similar discrepancies were consistently found in all HJ's that exhibited reasonable agreement between measured and reconstructed \( \tilde{h}(x) \) profiles. By changing the assumed \( N_i(x) \), we could have increased \( \Delta E_g \) by about 0.02 eV, at the expense of an increasing discrepancy between reconstructed and measured \( \tilde{h}(x) \), but still within acceptable limits. Any larger increase could not be justified.

We speculate that the lower conduction band discontinuities relative to the value of Dingle et al.1 are due to compositional grading. However, care is in order on this matter: our method measures a true electrostatic dipole moment. Such a moment would be present even in a HJ that is so widely graded that the conduction band has become almost flat. A flat conduction band in a widely graded heterojunction does not mean that there is no electrostatic potential difference. It simply means that electrostatic and chemical potential differences cancel each other locally. We would therefore expect our method to yield a finite value for an apparent conduction band discontinuity even for such a widely graded structure, although probably a smaller value than for an abrupt HJ.

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Size effects in MoSi2-gate MOSFETs

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Refractory metal silicide gate n-channel MOSFET's have been fabricated by rf sputtering from a hot-pressed MoSi2 alloy target. The annealed MoSi2 sheet resistance was 2 \( \Omega /\square \). The MOSFET's were fabricated using plasma etching, projection alignment, and a fully ion-implanted process. Typical values for a 1.7 \( \times \) 1.7-\( \mu \)m\(^2\) linear MOSFET are a threshold voltage of 1–1.5 V and a transconductance of 50–100 \( \mu \)mho. Short-channel (length and width) and substrate effects on the threshold voltage are demonstrated.

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Refractory metal\(^{1,2}\) and metal silicide\(^{3,4}\) gate devices are known to be compatible with standard MOS processes, and provide a higher speed capability. While refractory metals have higher conductivity, refractory metal silicides are oxidation resistant and can be used in two-level structures. In this letter, the fabrication and characteristics of short-channel (\(< 2 \mu m\)) MoSi2-gate MOSFET's are reported.

An integrated-circuit chip was designed containing two matrices of MOSFET's, linear and self-enclosed, with nominal channel dimensions varying from 1.25 to 10 \( \mu \)m in length and from 1.25 to 260 \( \mu \)m in width. A microphotograph of the processed chip is shown in Fig. 1 along with an SEM photograph of a MOSFET with approximately 2 \( \mu \)m channel length. To facilitate automated testing and to minimize external connections, the sources of all MOSFET's, the gates of MOSFET's of equal width, and the drains of MOSFET's of equal length are, respectively, in common.

The devices were made on Czochralski-grown, (100)-oriented, boron-doped, 2–3-\( \Omega \) cm Si wafers. Field oxide, about 6000 \( \AA \) thick, was used for device isolation. The field oxide was grown with an isoplanar process. During this step, a composite dielectric of 2000-\( \AA \) Si3N4 and 300-\( \AA \) SiO2 was