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Effect of impurity trapping on the capacitance-voltage characteristics of n-GaAs/N-AlGaAs heterojunctions

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We have studied the capacitance-voltage (C-V) characteristics of Schottky barriers on inverted n-GaAs/N-AlGaAs and normal N-AlGaAs/n-GaAs heterojunctions. Impurities introduced during film growth produced a negative sheet charge of 6.0×10^{11} cm^{-2} at the interface of the inverted n-GaAs/N-AlGaAs heterojunction. The effectiveness of GaAs quantum wells in trapping these impurities was investigated. GaAs quantum wells 20 Å wide were placed in intervals of 2500 Å for the first 0.75 μm of the AlGaAs layer; in the last 0.25 μm, the periodicity of the quantum wells was progressively decreased by half with the last quantum well placed at about 160 Å from the GaAs/AlGaAs interface. The resulting measured interface charge concentration of 4.4×10^{10} cm^{-2} is more than a magnitude lower than measured before the use of the quantum wells and is essentially at the limit of the accuracy of the C-V technique for this structure.

Although the GaAs/AlGaAs (so-called inverted) heterojunction has not achieved high performance in modulation-doped field-effect transistors, its properties are of considerable interest for other device applications. The inverted junction is also widely used for band discontinuity extraction by capacitance-voltage (C-V) analysis.[1-3] High-efficiency solar cells which make use of such heterojunction back-surface fields have been recently reported.[4] For both applications the properties of the interface are of considerable concern; interface traps may enhance minority-carrier recombination in solar cells and may adversely affect the accuracy of band discontinuity measurements. A comprehensive study of conduction-band discontinuities in GaAs/AlGaAs heterojunctions was recently reported by Okumura *et al.*[1] Using Kroemer's C-V technique,[2,3] they determined both the band discontinuity and interface charge density. These authors reported that the extracted band discontinuities were in error when the measured interface charge density exceeded 10^{11} cm^{-2}. Deep level transient spectroscopy measurements confirmed that the traps were localized at the GaAs/AlGaAs interface.[5] While the source of traps was not identified, Okumura *et al.*[1,5] believed the traps to be extrinsic since a larger trap concentration was obtained when growth was interrupted at the interface.

When extracting band discontinuities by C-V analysis, the inverted GaAs on AlGaAs (binary on top of ternary) heterojunction should be used in order to accurately judge the position of the interface from the measured apparent carrier profile.[2] The molecular beam epitaxy (MBE) growth of inverted modulation-doped GaAs on AlGaAs heterojunctions has exhibited inferior carrier mobilities in comparison to the normal AlGaAs on GaAs heterojunction.[6] Several possible causes for the poor mobility of the inverted heterostructure have been advanced. The poor mobility may be the result of a rough surface formed due to the difficulty of growing thick layers of AlGaAs with high crystalline quality.[7] A second possible explanation is the tensile strain perpendicular to the interface caused by the larger lattice constant of the AlGaAs.[8] Third, inferior mobilities may be due to impurities trapped in a thin layer of GaAs at the interface when the Al flux is terminated.[9] Drummond *et al.*[8] have shown that a 150-Å-thick AlGaAs/GaAs three period superlattice, in place of the undoped AlGaAs spacer layer, can improve the carrier mobilities by 6.5 times in the inverted heterostructure. In this letter we investigate the role of impurity trapping on the C-V characteristics of n-GaAs/N-AlGaAs (inverted) and N-AlGaAs/n-GaAs (normal) heterojunctions.

The MBE system used in this work was a Perkin–Elmer model PHI400. The inverted heterojunctions were grown with a 0.5-μm GaAs buffer layer at a substrate temperature of 580 °C. The AlGaAs layer was typically about 1 μm thick and grown at a substrate temperature of 700 °C. The first 200–300 Å of the 0.2-μm-thick top GaAs layer was also grown at 700 °C before the substrate temperature was reduced to 620 °C for the remainder of the growth. Growing the first 200–300 Å of GaAs at a temperature of 700 °C has been shown to reduce the sensitivity of interface sharpness to growth conditions.[7] The doping density of the GaAs and AlGaAs was approximately equal; both were doped at about 1×10^{17} cm^{-3}.

The heterojunctions grown were C-V profiled by the use of a MSI Electronics Inc. Model Hg-2 mercury probe. (When properly calibrated, this mercury probe is capable of reproducibility of better than 10%.[10]) Our initial heterojunctions exhibited the expected accumulation of electrons in the GaAs side and depletion of electrons in the AlGaAs side. During the course of this study, gas source MBE, using nitrogen taken from a liquid nitrogen dewar, was also being performed in the same system. The apparent carrier profile of a sample grown immediately following gas introduction (sample S1) showed no accumulation in the GaAs side. Heterojunction sample S2 grown the following day displayed a similar depleted interface as shown in Fig. 1. The cause of this depletion at the interface is thought to be a negative sheet charge at the interface of the heterojunction due to a layer of impurities. Miller *et al.*[11,12] have postulated the cause of such impurity layers as due to the impurities segregating at the surface during growth of the AlGaAs.

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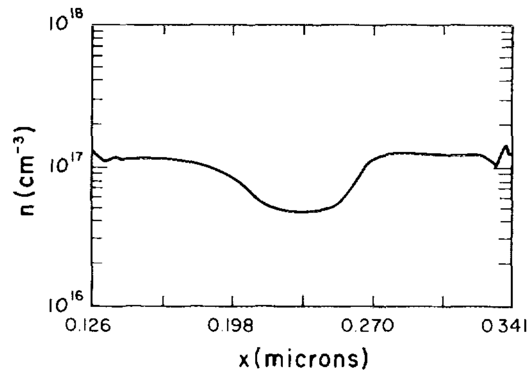

FIG. 1. Apparent carrier profile obtained from C-V measurements of sample S2 (inverted heterojunction).

When the top GaAs layer is grown, the impurities are trapped at the heterojunction interface. The impurities, believed to be introduced during the gas source MBE run, have not been identified at this time.

If the depletion was indeed due to impurities incorporating and segregating at the surface of the AlGaAs, the depletion at the interface should not have been observed if a normal heterojunction had been grown instead (i.e., ternary on top of binary). In the normal heterojunction the impurities would be trapped at the surface of the AlGaAs and the Schottky barrier would deplete through this thin layer of impurities. A normal heterojunction (sample S3) was grown using similar conditions as before and the resultant apparent carrier profile in Fig. 2 showed an accumulation layer on the smaller band-gap side and a depletion on the wider band-gap side as expected. This carrier profile supports the suspicion that the depletion at the interface was due to impurity contamination and then segregation at the surface of the AlGaAs. These observations support those recently reported by Okumura *et al.*[5] An inverted heterojunction grown after sample S3 still exhibited a depleted interface similar to sample S2. During the course of this work we found that after the first introduction of impurities the subsequent growth of inverted heterojunctions resulted in apparent carrier concentrations similar to sample S2.

Since it has been demonstrated that GaAs quantum wells trap impurities,[9,11,12] GaAs quantum wells placed periodically in the thick AlGaAs may be capable of trapping

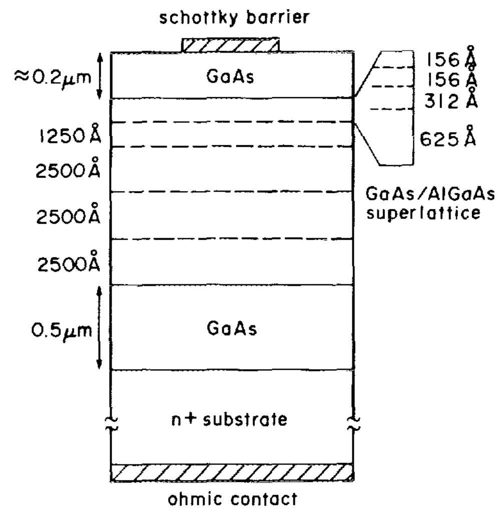

FIG. 3. Inverted heterojunction with GaAs quantum wells inserted in the AlGaAs layer. Thickness of the GaAs quantum wells is 20 Å with decreasing periodicity as it approaches the top heterojunction.

impurities away from the top heterojunction interface and hence reduce the interface charge. The GaAs quantum wells were chosen to be 20 Å wide and were placed in intervals of 2500 Å for the first 0.75 μm of the AlGaAs layer. In the last 0.25 μm, the periodicity of the quantum wells was progressively decreased by half as shown in Fig. 3, with the last GaAs quantum well placed at about 160 Å away from the interface.

Heterojunction sample S4 was grown with conditions similar to that of samples S1 and S2 except with the addition of the above described GaAs quantum wells placed in the AlGaAs layer. The resultant apparent carrier profile in Fig. 4, extracted from the C-V measurements, did indeed show an accumulation of carriers on the GaAs side of the heterojunction and a depletion on the AlGaAs side. These results suggest that the GaAs quantum wells trapped impurities and prevented them from accumulating on the top surface of the growing AlGaAs.

As mentioned earlier, a C-V technique introduced by Kroemer[2,3] can be used to extract the interface charge density and conduction-band discontinuity of a heterojunction. Using Kroemer's C-V technique, a negative interface charge of 6.0×10^{11} cm^{-2} was measured for heterojunction sample S2. The measured interface charge for sample S4 was

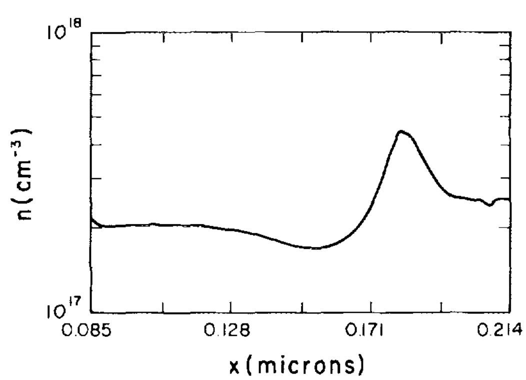

FIG. 2. Apparent carrier profile obtained from C-V measurements of sample S3 (normal heterojunction).

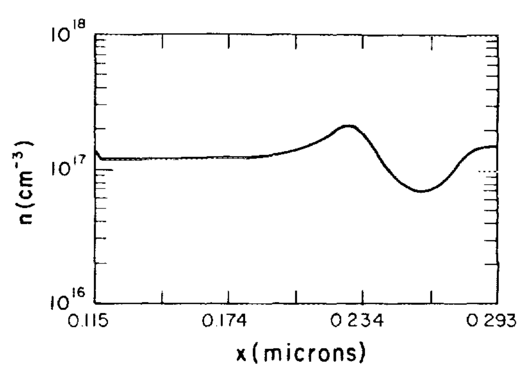

FIG. 4. Apparent carrier profile obtained from C-V measurements of sample S4 (inverted heterojunction with quantum wells).

4.4×10^{10} cm^{-2}, more than a magnitude lower than that measured before the use of the GaAs quantum wells. (This measured interface charge of 4.4×10^{10} cm^{-2} is essentially at the limit of the accuracy of the C-V technique for this structure.[13]) The measured conduction-band discontinuity for sample S4 ($GaAs/Al_{0.2}Ga_{0.8}As$ heterojunction) was 0.121 eV with a deviation of less than 4 meV across the substrate. This measured discontinuity of 0.121 eV corresponds to a $\Delta E_c = 0.5\Delta E_G$ for $x = 0.2$.

In conclusion, we have shown that impurity trapping at the interface of the inverted GaAs/AlGaAs heterojunction produces high interface charge. These results support the recent observations of Okumura *et al.*[5] We also demonstrated that the use of a few GaAs quantum wells placed periodically in the AlGaAs is an effective means for producing low interface charge inverted heterojunctions even in the presence of impurity contamination. Capacitance versus voltage analysis indicates that the technique is capable of an interface charge reduction of an order of magnitude. The technique may be of use in device applications that require inverted GaAs/AlGaAs heterojunctions with thick AlGaAs layers.

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[1]H. Okumura, S. Misawa, S. Yoshida, and S. Gonda, Appl. Phys. Lett. **46**, 377 (1985).

[2]H. Kroemer, W. Y. Chien, J. S. Harris, Jr., and D. D. Edwall, Appl. Phys. Lett. **36**, 295 (1980).

[3]H. Kroemer, Appl. Phys. Lett. **46**, 504 (1985).

[4]R. P. Gale, John C. C. Fan, G. W. Turner, and R. L. Chapman, *Proceedings of the 1984 Photovoltaics Specialist Conference* (IEEE, New York, 1984), p. 1422.

[5]H. Okumura, S. Misawa, and S. Yoshida, The Second International Conference (Yamada Conference) on Modulated Semiconductor Structures, Kyoto, Japan, Sept. 9–13, 1985.

[6]H. Morkoç, L. C. Witkowski, T. J. Drummond, C. M. Stanchak, A. Y. Cho, and B. G. Streetman, Electron. Lett. **16**, 753 (1980).

[7]W. Kopp, S. L. Su, R. Fisher, W. G. Lyons, R. E. Thorne, T. J. Drummond, H. Morkoç, and A. Y. Cho, Appl. Phys. Lett. **42**, 615 (1983).

[8]T. J. Drummond, J. Klem, D. Arnold, R. Fisher, R. E. Thorne, W. G. Lyons, and H. Morkoç, Appl. Phys. Lett. **42**, 615 (1983).

[9]S. R. McAfee, D. V. Lang, and W. T. Tsang, Appl. Phys. Lett. **40**, 520 (1982).

[10]P. S. Schaffer and T. R. Lally, Solid State Technol. **26**, 229 (1983).

[11]R. C. Miller, W. T. Tsang, and O. Munteanu, Appl. Phys. Lett. **41**, 374 (1982).

[12]P. M. Petroff, R. C. Miller, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **44**, 217 (1984).

[13]K. L. Tan, MSEE thesis, Purdue University, August 1985.