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Electrochemical Capacitance-Voltage Analysis of Delta-Doped Pseudomorphic High-Electron-Mobility Transistor Material

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This work shows how electrochemical capacitance-voltage (EC-V) measurements can be used to evaluate delta-doped pseudomorphic high electron mobility transistor material. These EC-V measurements are compared with magnetic-field-dependent Hall effect (M-Hall) measurements and a self-consistent Poisson/$k \cdot p$ calculation of the band structure and electron concentration. The EC-V technique can clearly delineate the cap layer, the delta-doped layer, and the $In_xGa_{1-x}As$ channel layer, whereas the M-Hall method characterizes only the cap and $In_xGa_{1-x}As$ channel layers. The amount of electron charge seen by the EC-V and M-Hall measurements show good agreement with theory.

Conventional capacitance-voltage (C-V) measurements, in which a stepped reverse-bias voltage is used to successively deplete small regions of a semiconductor layer, have long been used to determine dopant concentration profiles in relatively thick semiconductor materials. By applying the so-called depletion approximation to Poisson's equation, an apparent concentration $N_{cv} = C^3/e\epsilon(dC/dV)$ at an apparent depth of $z_{cv} = \epsilon/C$ provides a profile which approximates the true profile quite well except for regions in which N_{true} varies significantly within a Debye length. Fortunately however, even when N_{cv} is distorted, the apparent charge differential $dQ = eN_{cv}dz_{cv}$ is equal to the true charge differential $dQ = CdV = eN_{\text{true}}dz_{\text{true}}$, as is easily shown from the above equations, so that the *integrated* charge of the measured C-V profile is correct.

In recent years, the conventional C-V method has been applied both to $Al_xGa_{1-x}As/GaAs$ heterostructure junctions[1] and also to sheet-charge ("delta-doped") layers.[2-5] In the latter case, when electrons exist in quantized levels, the Debye-length limitation no longer holds, and the C-V resolution is related to the wave-function extent.[4] Since present day high-speed devices like pseudomorphic high electron mobility transistors (pHEMTs) contain a highly doped cap layer, which leads to diode breakdown for high reverse biases, a different technique called electrochemical C-V (EC-V) is applied.[6] The EC-V method substitutes stepped surface etching for stepped reverse biasing. The whole experiment is carried out at a low bias, so that breakdown is not a problem. Even though the experimental procedure differs from conventional C-V measurements, the analysis is basically equivalent. Here we demonstrate, for the first time to our knowledge, that the EC-V technique can separate the cap layer, the delta layer, and the $In_xGa_{1-x}As$ channel layer [containing a two-dimensional electron gas (2DEG)]. The EC-V results agree with theoretical modeling for the combined sheet charge of the delta and 2DEG layers. The results are also consistent with magnetic-field-dependent Hall-effect (M-Hall) data, which can characterize the cap and 2DEG regions.

The EC-V measurements were made by using a PN4200 BIO-RAD system with 0.1 M Tiron as the electrolyte and a 3-mm-diam sealing ring. These conditions gave relatively good uniform etch rates. Bias conditions were carefully chosen so that leakage currents were minimized for accurate measurements. The system was calibrated with conventional Hall measurements using thick (~1 μm) uniformly doped molecular beam epitaxial (MBE) GaAs:Si layers doped at 3×10^{18} cm^{-3}, so as to minimize errors due to depletion. The thickness was calibrated against reflection high-energy electron diffraction (RHEED) oscillations carried out in the MBE system.

Figure 1(a) shows the pHEMT structure with the delta-doped layer in the barrier separated from the channel by 45 Å. The listed thicknesses and concentrations are nominal. Figure 1(b) gives theoretical results of the energy-band and electron-concentration profiles. The electron distribution and potential were calculated from a self-consistent $k \cdot p$ formulation. The electron wave functions, from which the electron distribution is calculated, were obtained from the $k \cdot p$ model. The Hartree part of the potential was calculated from the Poisson equation and the exchange correlation part from density functional theory within the local-density approximation.[7] The model assumes that all the shallow donors are ionized. Note that the integrated charge is larger in the well (2DEG) than in the delta-doped region for the present structure, which has a 45 Å spacer.

Figure 1(c) shows the EC-V results for the sample of Fig. 1(a) (solid line). In Fig. 1(c) we note the cap layer at 300 Å and then an asymmetric structure is seen between 500 and 700 Å. We believe the small shoulder of the asymmetric peak on the shallow side represents the delta-doped barrier region and the larger peak at 640 Å is due to the 2DEG in the well region. This explanation agrees with the theoretical profile of Fig. 1(b) in a qualitative sense. We also have included mea-

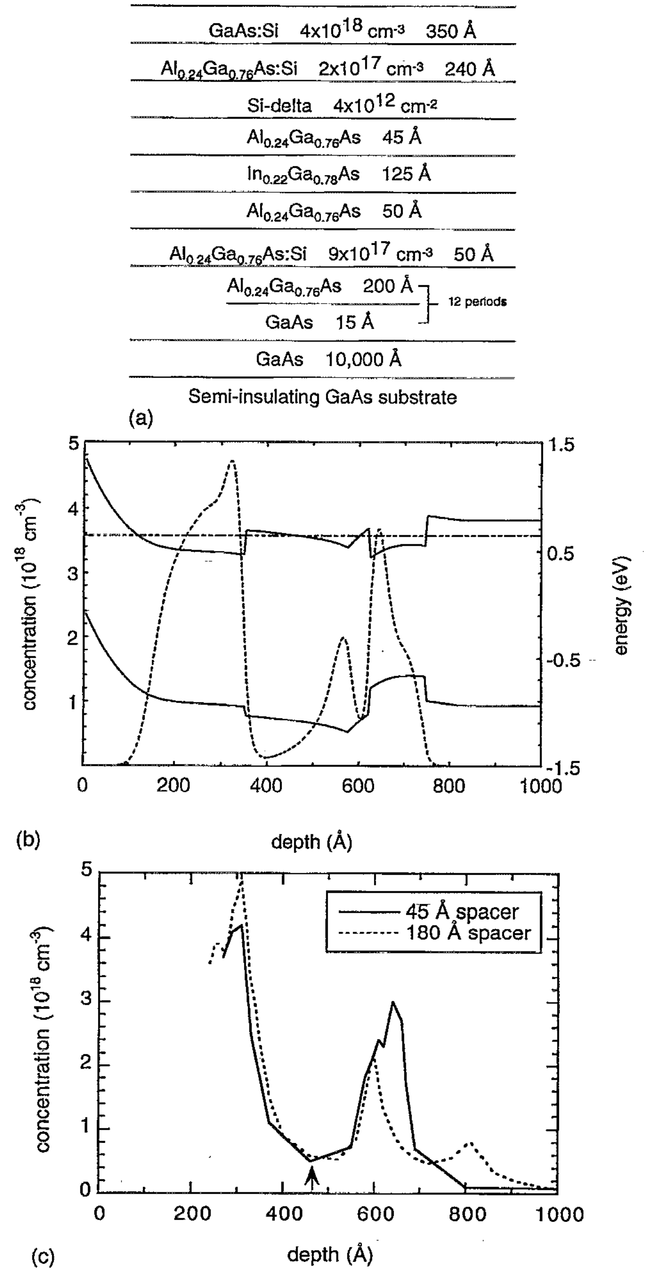

FIG. 1. pHEMT with a 45 Å spacer: (a) layer structure; (b) theoretical calculation showing the energy bands (solid line), the carrier concentration (dashed line), and the Fermi level (chain line); (c) EC-V measurement with an arrow showing where integration begins.

TABLE I. The electron concentration, in units of 10^{12} cm^{-2}, measured by the EC-V and M-Hall techniques, compared to theory for a pHEMT with a 45 Å spacer layer.

Region	EC-V	M-Hall	Theory
Cap	···	5.4±2	7.6
δ layer	···	···	1.6
2DEG	···	3.1±0.2	3.0
δ+2DEG	4.5±0.3	···	4.6

sured data from a nominal 180 Å spacer sample that shows two completely separated peaks at 600 and 810 Å depth, respectively. These data demonstrate that we are actually able to delineate the delta-doped layer in the barrier (at 600 Å) and the 2DEG in the well (at 810 Å). To compare the 45 Å layer with theory we arbitrarily chose to integrate the charge from the concentration minimum ($dN_{cv}/dz_{cv}=0$) between the cap layer and the delta-doped layer effectively to infinity for both the theoretical and measured results, since effects from the doped cap are assumed negligible beyond this minimum. Using this method the total delta plus 2DEG integrated charge is consistent for the above theoretical and measured (EC-V) results, as shown in Table I. However, not enough resolution is available using EC-V to clearly separate out the individual delta and 2DEG contributions for 45 Å spacer material.

Note that in the present case we have not etched through the cap by the time the depletion region is through the 2DEG. In cases for which the cap is etched through at this point, the measured charge in the delta-doped region will be lower due to the lack of screening from the electrons in the cap. In other words, to accommodate the potential at the etched surface, some of the charge in the delta will have to flow to the surface states if these states are not filled with cap electrons.

Room temperature M-Hall measurements were carried out using magnetic fields of 2, 10, and 16 kG. The technique is described elsewhere,[8] but basically can separate the carrier concentration and mobilities in two conductive layers, unlike conventional Hall-effect measurements. In this case we determine concentrations and mobilities n_{2DEG}, μ_{2DEG}, n_{cap}, and μ_{cap}, but not the parameters in the delta since its electrons have too low a mobility (~100 cm^2/V s) to be observed. Results are given in Table I, and it is seen that n_{2DEG} agrees well with theory. On the other hand n_{cap} usually cannot be determined with good accuracy by the M-Hall technique. Fortunately, $\rho_{cap}=(en_{cap}\mu_{cap})^{-1}$ is determined more accurately, and since $\mu=1500\pm500$ cm^2/V s for nearly all GaAs cap layers, we can determine n_{cap} from this value of μ_{cap} and the measured ρ_{cap}. This technique leads to satisfactory agreement between measurement and theory for n_{cap}, especially since the theory does not include the possibility of GaAs/$Al_xGa_{1-x}As$ interface charge for this particular case.

In conclusion we have compared EC-V measurements with M-Hall measurements and theoretical calculations to show the usefulness of the EC-V technique for exploring the properties of delta-doped pHEMT material. The EC-V measurements can delineate the cap, delta-doped, and 2DEG regions. They are also useful for determining the total doping in the delta-doped and $In_xGa_{1-x}As$ regions, and for qualitatively showing the amount of charge transferring from the delta-doped layer to the 2DEG region.

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