Evidence for internal electric fields in two variant ordered GaInP obtained by scanning capacitance microscopy

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Single and two variant ordered GaInP samples are studied in cross section with the scanning capacitance microscope. Our study shows significant differences in the electronic properties of single and two variant GaInP. In unintentionally doped, ordered two variant samples, both n and p-type like domains are observed with the scanning capacitance microscope. In contrast, a spatially uniform capacitance signal is observed in unintentionally doped single variant ordered GaInP. These microscopic capacitance observations can be qualitatively explained by bend bending or internal electric fields. © *1996 American Institute of Physics.* [S0003-6951(96)00952-7]

During recent years, atomic ordering has been observed in a wide range of III-V semiconductor alloy systems.[1] The most common type of ordering in GaInP is the CuPt-type ordering which was observed by Gomyo *et al.*[2] In the ideal case, $(GaP)_1(InP)_1$ superlattice forms along a [111] direction. Ordering reduces the band gap[3] and splits the heavy-hole light-hole degeneracy at the valence band maximum. The ordering in GaInP affects both the optical[2] and electrical[4] properties of the material and is interesting and important for optoelectronic devices. In this work, we report new microscopic imaging results with the scanning capacitance microscope (SCM) which show dramatic electronic variation on a submicrometer scale in ordered two variant samples, while no variation is observed in single variant samples. These results support the model that internal electric fields are present in two variant films.

Samples 1 and 2 were grown by organometallic vapor-phase epitaxy (OMVPE) on (001) GaAs (n-type) using trimethylindium, trimethylgallium, and PH_3. To produce highly ordered materials, the samples were grown at 670 °C. The growth rate was 5.5 μm/h. The GaAs substrate misorientation from (001) toward $[\bar{1}10]$ was 0° for sample 1. Sample 2 was grown with a 4° misorientation. Sample 1 contains both variants present in roughly equal quantities. Only a single variant of ordered GaInP is present in sample 2. All GaInP epilayers and GaAs buffer layers are nominally undoped, with a typical (unintentional) background doping level of 5×10^{15} cm^{-3} n type for GaInP epilayer and 1×10^{15} cm^{-3} p type for GaAs buffer layer, as measured by electrical chemical capacitance-voltage (C-V) measurement. The epilayer thickness is approximately 10 μm for sample 1 and 6 μm for sample 2. The thickness of the buffer layer between the epilayer and the substrate of all samples is approximately 0.6 μm. All samples were cleaved for cross-sectional imaging.

In the SCM experiment,[5] a metal-coated silicon tip is brought to the surface of the sample and a contact mode atomic force microscope (AFM) is used to maintain the tip-sample distance and scan the tip across the sample. The AFM/SCM instrument used to perform these measurements is a Digital Instrument Dimension™ 3000. A sketch of the experimental arrangement is shown in Fig. 1. The SCM tip is inductively grounded and a 98 kHz ac bias voltage is applied to the sample. The tip and sample in the SCM experiment form a metal–insulator–semiconductor (MIS) system. ($C-V$) characteristics of the MIS system vary depending on the physical properties of the semiconductor surface.[6] In depletion, the majority carriers are depleted from the semiconductor surface. The total capacitance includes the series capacitance of the insulator and the semiconductor depletion layer. The depletion layer width depends on the doping concentration, the doping type, and the applied voltage. The depletion layer widens and the total capacitance falls as the applied tip/sample voltage becomes more positive for a n-type semiconductor and more negative for a p-type semiconductor. As a result, the slope of the $C-V$ curves of the MIS system has a different polarity for the two types of doping.[6] In the SCM experiment, an ac bias is applied to the sample and the capacitance change (ΔC), caused by the applied ac bias voltage, is measured by a high sensitivity capacitance sensor. This change is detected by a lock-in amplifier. The experiment was arranged such that a positive lock-in output voltage is observed for n-type samples and a negative is observed for p-type samples.

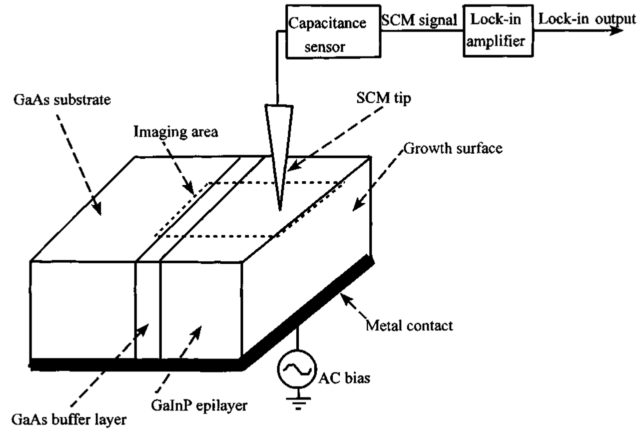

FIG. 1. A schematic of the SCM setup.

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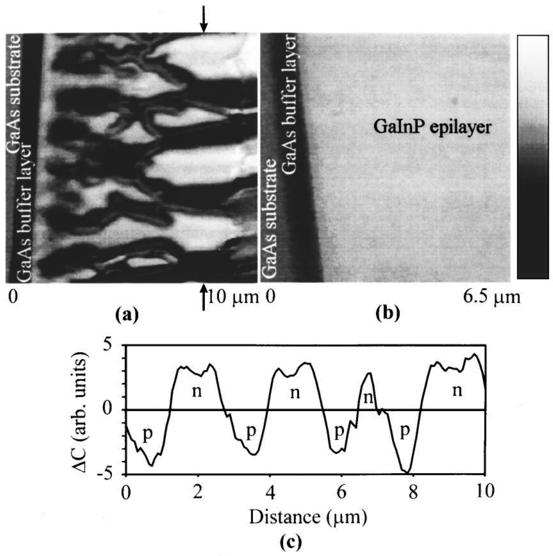

FIG. 2. (a) and (b) ΔC images of a (110) cross section surface of a cleaved sample 1 (two variant GaInP) and sample 2 (single variant GaInP) respectively. (c) A line-cut taken vertically along arrows on the epilayer shown in (a). The positive and negative lock-in output signal correspond to n-type and p-type, respectively.

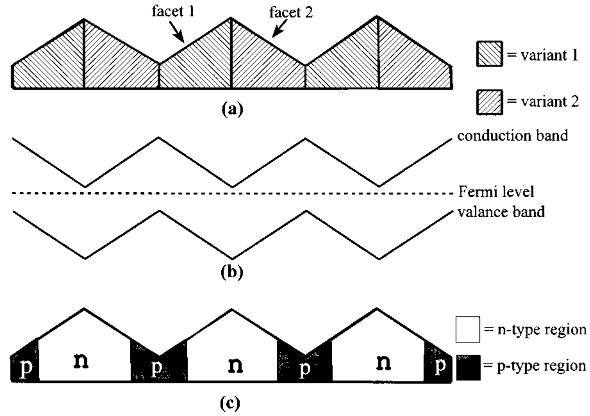

FIG. 3. (a) A sketch of an idealized (110) cross section through the (001) surface. The two ordered variants are found in complementary regions corresponding to opposite-facing facets of the hillock. (b) A qualitative sketch of the band diagram corresponding to (a) using internal electric fields. (c) Correlation between the n-type and p-type regions and topography.

A capacitance change (ΔC) image, obtained by the SCM, on the (110) surface of cleaved sample 1 is shown in Fig. 2(a). The image area of Fig. 2(a) is 10 μm by 10 μm and the peak to peak topographic variation on the cleaved surface is less than 40 nm. The applied bias between the SCM tip and the sample is 2 V peak at 98 kHz. In Fig. 2(a), the light color represents positive lock-in output signal which corresponds to n-type $C-V$ behavior and dark color represents negative lock-in output signal which corresponds to p-type $C-V$ behavior. The nearly vertical dark strip on the left side of Fig. 2(a) is a GaAs buffer layer which is 0.6 μm thick and shows p-type (negative lock-in output signal) response to the SCM. Left of the buffer layer is the GaAs substrate and it shows a uniform small positive lock-in output signal, which agrees with its n-type doping. To the right of the GaAs buffer layer is the GaInP epilayer which is approximately 10 μm thick. It can be seen that the capacitance change in this GaInP epilayer is very nonuniform. Both n-type (light color) and p-type (dark color) like regions appear in this GaInP epilayer, which is nominally undoped, with a typical (unintentional) background doping of n type. The n-type like regions are small near the substrate and grow larger near the middle of the epilayer. The p-type like regions are typically smaller than the n-type like regions near the growth surface. The spaghetti like regions (approximately zero lock-in output signal) between the n and p-type like regions may be intrinsic or built in depletion regions. Figure 2(c) is a line cut taken vertically along arrows on the epilayer shown in Fig. 2(a). It shows the capacitance change variation in the n- and p-type like regions.

The top surface topography of sample 1 has been observed by the AFM. It is composed of distinct hillocks which are typically 2–5 μm wide, 2–20 μm long, and 0.05–0.2 μm high. Our measurements agree with the measurement by Friedman *et al.*[7] An idealized (110) cross section is shown in Fig. 3(a) (proposed by Friedman *et al.*). To experimentally determine the relation between the n- and p-type like regions seen by the SCM and the surface structure, a cross-sectioned sample is tilted at an approximate angle of 45° and the tip is scanned across the cleaved edge. Under this arrangement, the topographic and capacitance change image from both the cleaved (110) cross section and (001) top surface can be obtained simultaneously and directly correlated. The topographic structures (hillocks) of the (001) surface and capacitance change on the (110) surface are compared directly at the interface. More than ten different locations were imaged in this mode. We found that the n- and p-type like regions are centered under the peaks and valleys of the top surface hillocks, respectively.

In order to compare single and two variant ordered GaInP samples, sample 2 (single variant) was imaged by the SCM. Figure 2(b) shows the capacitance change image (6.5 $\times$ 6.5 μm) on a cleaved (110) surface of sample 2 (single variant). The GaInP epilayer shows uniform n-type (positive lock-in output) SCM signal. No p-type like regions appear in this GaInP epilayer.

There are at least two effects that could explain these observations. The first is an effect first observed[8] by Alonoso *et al.* and later studied theoretically[9] by Froyen *et al.* Froyen *et al.* have calculated that ordered GaInP has a strong macroscopic electric polarization along the (111) direction resulting in an internal electric field in ideally ordered GaInP as large as 16 mV/Å at 0 K.[9] Pyroelectricity, related to this polarization field, has been observed experimentally in single variant ordered GaInP.[8] Friedman *et al.* have shown that the two ordered variants exist in the two complementary regions corresponding to the opposite-facing facets of the surface hillocks.[7] Figure 3(a) shows an idealized (110) cross section of a two variant ordered GaInP and the relation between the two ordered variants [variant 1 (1$\bar{1}$1) and variant 2 ($\bar{1}$11)] and the facets 1 and 2 (topography) as shown by Friedman *et al.* Variant 1 sits below facet 1 of the hillock and variant 2 sits below facet 2 of the hillock.[7] If the calculations of Froyen *et al.* are applied to this case, the internal electric field along [$\bar{1}$10], which is a component of a field along the (111) direction, in variant 1 and 2 point to the left and right respectively in Fig. 3(a).[9] Therefore, the conduction and valence bands should be bent and that the Fermi level should be near the conduction band at the peak of the hillock and near the valence band at the valley of the hillock as shown in Fig. 3(b). If the band bending is significant enough, both n- and p-type like regions will show up in the two variant sample as shown in Fig. 3(c). Figure 3(c) is drawn using the band structure in Fig. 3(b). The p-type regions appear below the bottom of the grooves and n-type region appear below the peaks. This model is consistent with our SCM experimental results. Note that the internal field along the [001] direction, which is a component of a field along the ⟨111⟩ direction, in variants 1 and 2 point in the same upward direction. We believe that this internal electric field will be screened by charges at the top surface and free carriers from the substrate at the GaInP/GaAs interface. In single variant ordered GaInP, it is expected that the uniform internal electric field will be also screened in a similar way.[9] As a result, band bending in single variant GaInP will not be seen by the SCM.

The other possible source for internal electric fields could be dopant segregation[10,11] on the nonplanar growth surfaces of two variant samples. Our results could be explained if more n-type and p-type dopants preferentially stay on the top and bottom of the hillocks respectively in two variant GaInP. Single variant samples typically have planar surfaces and the dopant segregation should not occur during growth. Therefore the ΔC signal should be uniform. We cannot conclude here whether the internal electric field is a polarization effect or due to dopant segregation. Further work is in progress.

In summary, the SCM has been used to study single and two variant GaInP. The measurements have been made in cross section and at room temperature. The results clearly show that both n and p-type like regions appear in unintentionally doped two variant GaInP. This can be qualitatively explained by the existence of internal electric fields or local band bending.

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