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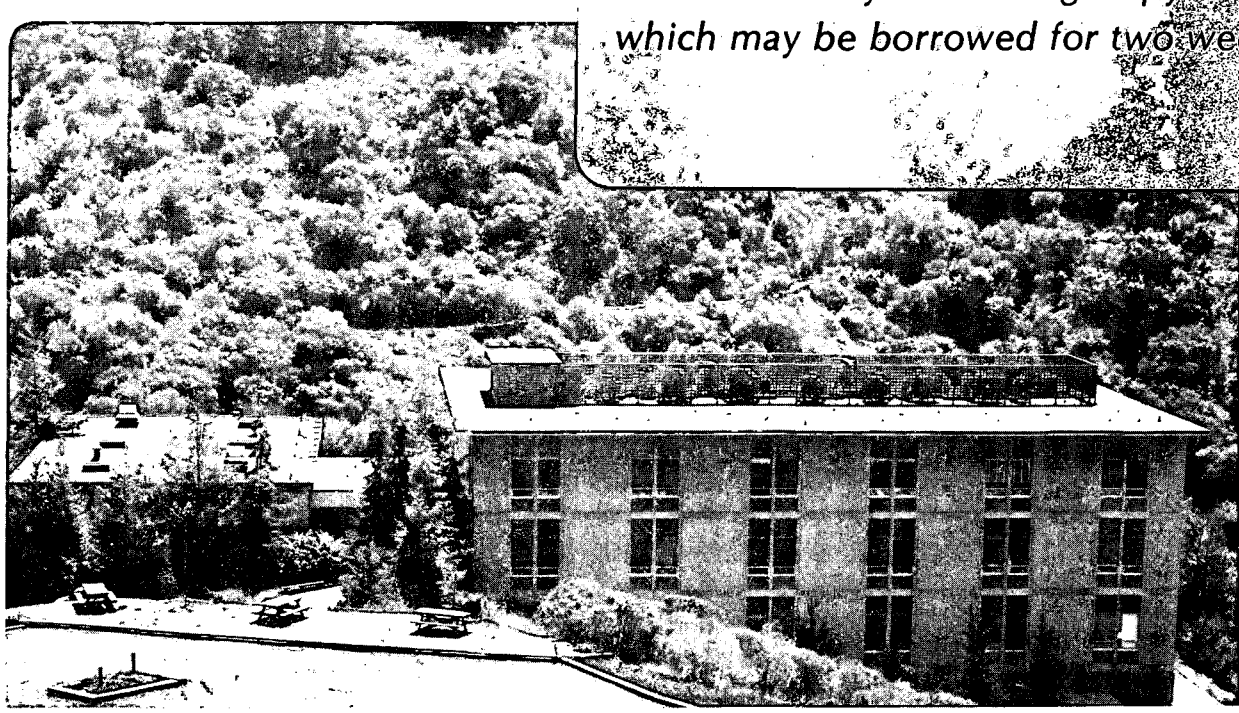

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SURFACE FACETING OF (110) GaAs: ANALYSIS AND ELIMINATION

L. Parechanian-Allen[1,2], E.R. Weber[1], J. Washburn[2] and Y.C. Pao[3]

[1]Dept. of Materials Science, Univ. of Calif., Berkeley, Ca. 94720
[2]Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, Ca. 94720
[3]Varian Associates, Microwave Division, Santa Clara, Ca.

ABSTRACT

A systematic study has been made on (110) GaAs grown by molecular beam epitaxy. This work represents the first systematic investigation of commonly observed faceting on the (110) GaAs surface which has led to the consistent elimination of the defects. This study involved the analysis of facet geometry, a kinetic model of initial facet formation, and the electrical and optical analysis of facet free (110) GaAs. The latter was obtained with proper growth conditions and a Ga rich surface exposure from a GaAs substrate angled 6° toward $(11\bar{1})$Ga.

INTRODUCTION

Molecular beam epitaxy (MBE) is a well established, ultra-high vacuum technique of crystal growth that is known for its excellent epitaxial quality and precise dopant profile control[1]. GaAs has traditionally been grown on (100) GaAs substrates largely due to the natural cleavage planes associated with that surface as well as the wide range of growth conditions which allow smooth epitaxial layers for device fabrication. The anisotropic behavior of (110) GaAs, however, makes that orientation especially valuable for, e.g., improved efficiency of electron avalanche behavior for microwave devices as well as modulator/polarizer applications for integrated optics[2,3]. In addition, the recent interest of GaAs growth on Si makes the non-polar (110) epitaxial surface a viable candidate to eliminate the sheet charge associated with MBE growth of the polar (100) GaAs on Si[4].

Until this investigation, all published reports of (110) GaAs epitaxial layers grown by MBE have shown faceted surfaces with poor device performance[5-8]. This study has resulted in the understanding of facet alignment and geometry with respect to the (110) GaAs surface, a kinetic modeling of initial facet formation, and a method to eliminate facet formation during MBE growth. The latter depends on the proper growth conditions and exposure of only stable Ga ledges on the GaAs substrate to initiate planar growth for the MBE process. Experiments described in this paper support our model of initial facet formation. The epitaxial films were investigated by scanning electron microscopy (SEM), transmission electron microscopy (TEM), convergent beam electron diffraction (CBED), AUGER microscopy, Laue x-ray diffraction, low temperature Hall effect, capacitance-voltage (CV) and liquid He photoluminescence (PL) techniques.

EXPERIMENTAL

Growth of (110) and simultaneous (100) GaAs standards took place in a Varian Gen II MBE machine equipped with a dual wavelength infrared pyrometer. The optimal growth parameters of substrate temperature (570°C), arsenic overpressure (As/Ga 15), and preferred growth rate (1.4μm/hr) were previously established[8]. All (110) and (100) GaAs epitaxial layers grown on semi-insulating substrates were doped with Si, $N_d \approx 5 \times 10^{15}/cm^3$. The typical faceting on the epitaxial layers under all growth conditions are shown in the SEM image of Figure 1a. Careful analysis of the facets by

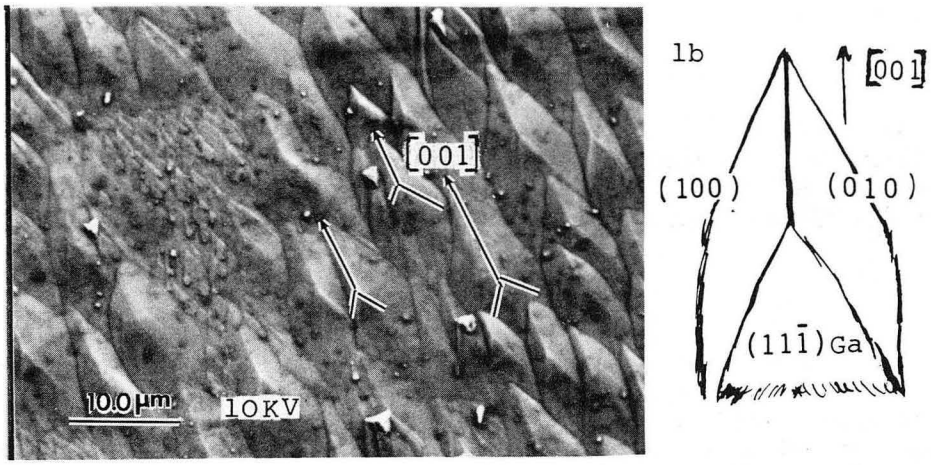

FIGURE 1. Faceting on (110) GaAs. Facet orientation and side plane indices are shown.

TEM, SEM tilting experiments, CBED, and AUGER microscopy determined the geometry of the facets with respect to the (110) GaAs crystal, the exact polarity of the facet back planes, and the overall facet chemical composition. Crystallographic orientations were determined with respect to the standard stereographic projection consistent with [9].

In order to examine the initial facet formation on the (110) GaAs surface, 100Å, 700Å and 1500Å epitaxial layers were grown and the surfaces examined with SEM as shown in Figure 2. A kinetic model of facet formation was developed from both the facet geometry and initial facet formation studies.

The model for facet formation was examined by growth of GaAs on off-axis (110) semi-insulating substrates which were angled 6° towards (100), 6° towards (010), 6° towards (111), and 6° towards (11$\bar{1}$) as can be seen on a standard (110) stereographic projection. The orientations were verified by Laue x-ray diffraction. 100Å, 700Å and 1500Å of epitaxial layers were grown on these substrates of different ledge types and results from each of these orientations are shown in Figure 3. Only one of the angled substrate types provided the facet free epitaxial growth[9]. This was consistent for 1μm of growth, as well, and was verified by SEM and TEM studies. CBED determined the exact nature of the ledges on the successfully angled (110) GaAs substrate.

Facet free epitaxial films were examined by variable temperature Hall effect as shown in Figure 4. Facet free epitaxial layers are compared with faceted (110) and (100) standard material. Ohmic contacts were made from In dots alloyed at 420°C for 20 mins. in a nitrogen atmosphere. Doping levels were confirmed by CV measurements. Liquid He Pl results support the high quality of epitaxial films obtained when compared with simultaneously grown (100) GaAs epitaxial standards.

RESULTS

As indicated in Figure 1, the facets were found to align along [001] with sides of (010), (100) and a back (11$\bar{1}$)Ga surface, the latter determined with a careful CBED analysis[10]. Initial facet formation studies on the (110) surface as shown in Figure 2 determined that facets begin with $\leq$ 100Å of epitaxial growth. By 700Å, the surface is replete with developed facets, and at 1500Å the facets had continued to grow and overlapped one another.

In Figure 3, the off-axis GaAs epitaxial layer morphology shows no improvement for the angled substrate 6° towards either (100) or (010). This angling exposed ledges that were non-polar in nature, i.e. both Ga and As atoms were present. The substrate angled 6° towards (111)As, as determined

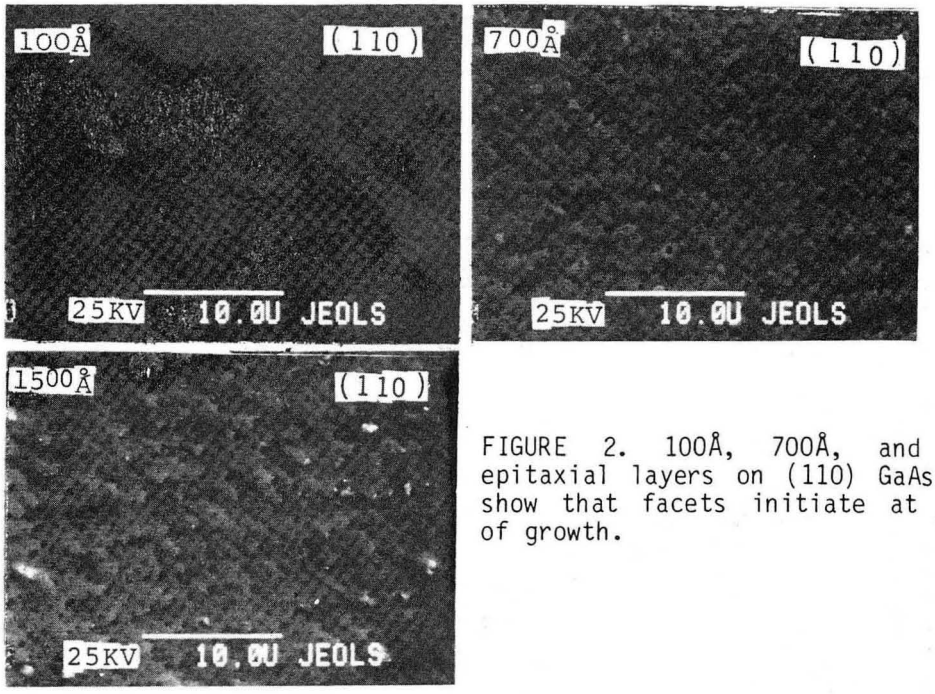

FIGURE 2. 100Å, 700Å, and 1500Å epitaxial layers on (110) GaAs which show that facets initiate at $\leq$ 100Å of growth.

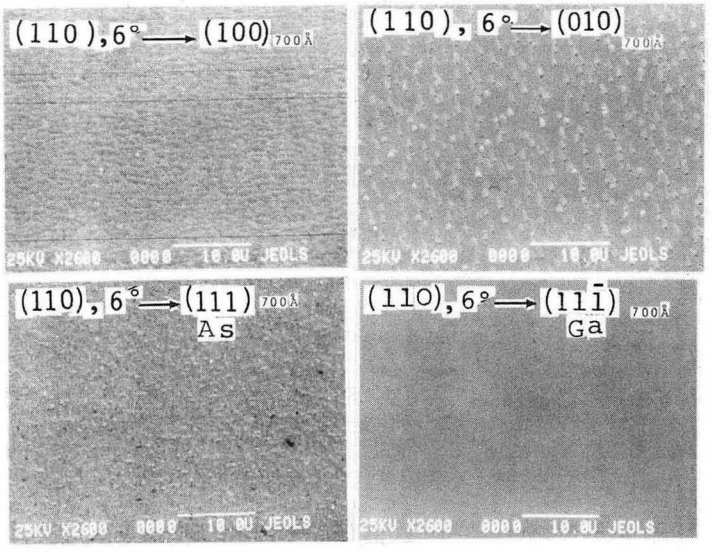

FIGURE 3. 700Å of epitaxial growth on angled substrates toward {100}, (11$\bar{1}$)Ga and (111)As.

by CBED, also provided faceted epitaxial layers by 100Å of growth. The ledges were of As rich polarity. Only the substrate angled 6° toward (11$\bar{1}$)Ga provided the stable Ga rich ledges necessary for two-dimensional or planar MBE growth.

In the Hall effect plots of Figure 4, the electron concentration as a function of temperature show that the dominant deep level ~ E_C-0.29 eV[8]

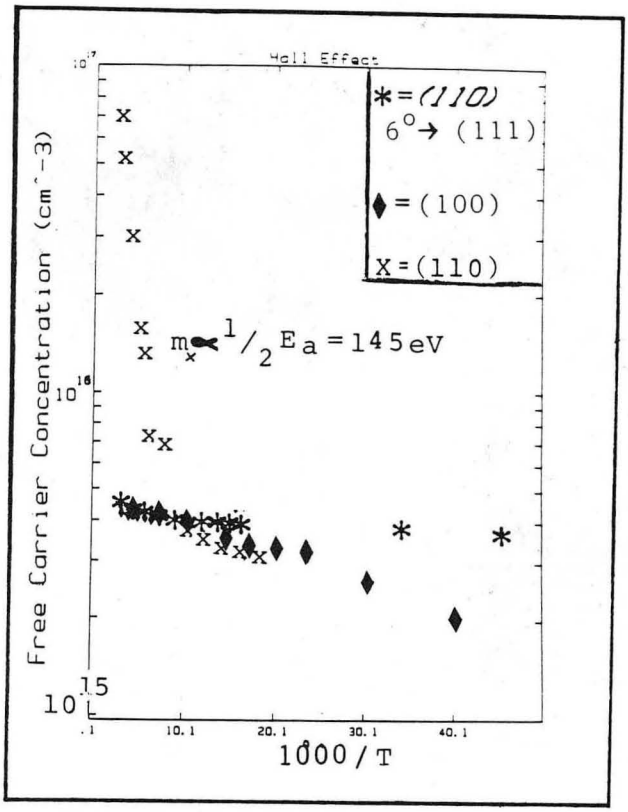

FIGURE 4. Variable temperature Hall effect for faceted (110) GaAs MBE material, non-faceted (110) MBE GaAs, and (100) GaAs standard MBE material.

is not present in the facet free material and doping levels are predictable. Room temperature electron mobility for the facet free (110) GaAs is ~5700 cm^2/V-sec which compares very well with typical (100) material values of ~5900 cm^2/V-sec. PL results showed a strong exciton luminescence peak (1.514eV) and a low neutral acceptor transition peak (1.490eV) which compared favorably with the (100) GaAs epitaxial standard, indicative of device quality layers.

DISCUSSION

The results of the facet geometry and initial facet formation on both the (110) and 6° off-axis films suggest that faceting of the GaAs epitaxial layer begins with random chemisorbtion of the first Ga and As pair on the substrate surface which creates the next atomic layer. As shown in Figure 5, the bonding of the Ga-As pair on the (110) surface then exposes both $(11\bar{1})$Ga and (111)As to the incoming molecular species. The low sticking coefficient of the incoming As atoms[1] makes it such that the latter species relies on the presence of chemisorbed Ga atoms in order to bond to the GaAs surface. Therefore, the $(11\bar{1})$Ga surface exposed by the initial Ga and As pair in place on the (110) surface provides the site for the next As and Ga pair, and so on. Facets begin to form from this $(11\bar{1})$Ga site as it continues to grow both two and three dimensionally, the facet sides filling in with a resulting {100} exposure. Thus, the rate of deposition of the incoming molecular species does not have an effect on the facet formation, a fact experimentally noted[8], as the facets grow at a rate proportional to the Ga and As fluxes.

When the substrate is angled such that ledges are exposed every 8 atomic layers, the type of ledge exposed is decisive in the quality of the resulting epitaxial layer. For the substrates angled 6° toward {100}, both As and Ga atoms are exposed on the ledges. While ledge sites can provide a

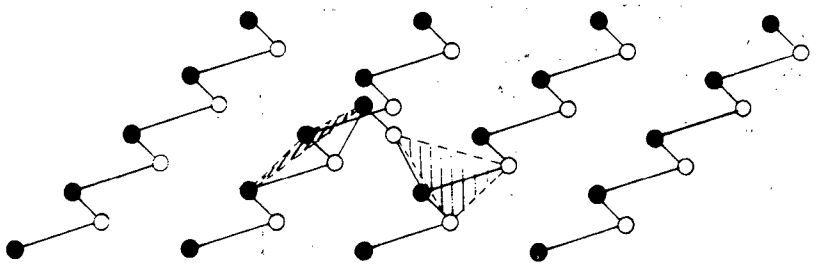

FIGURE 5. Schematic of random chemisorbtion of Ga-As pair on (110) surface exposing planes of (111)As and $(11\bar{1})$Ga.

thermodynamically favorable site for MBE palnar growth to initiate, the non-polar nature of the ledges offers little improvement over the non-polar GaAs (110) surface. When Ga and As pairs chemisorb on the ledges or the (110) substrate, facets begin to form from the exposed $(11\bar{1})$Ga surfaces. For the substrate angled 6° toward the (111)As, ledges of all As are exposed. With the tendency of the As atoms to desorb, the ledges are once again non-polar in nature and faceting occurs as the epitaxial layer grows. Only the exposure of Ga ledges on the (110) surface allows planar growth to procede, as the As atoms find the attraction to the Ga atoms already in position on the surface and are the first species to chemisorb[11]. The ledges provide the thermodynamically favorable site for two-dimensional growth of the epitaxial layer and the fast growing $(11\bar{1})$Ga are in position as ledges on the (110) surface. Facets do not form and excellent morphology and electrical and optical behavior results.

CONCLUSION

A thorough characterization of the faceted and non-faceted epitaxial layers by microscopy, electrical, optical, and chemical methods was necessary to understand the facet geometry and initial (110) GaAs facet development. This systematic approach to defect analysis has led to the consistent growth of facet free (110) GaAs. The successful MBE GaAs layers allow for device development and fundamental studies which can take advantage of the unique properties of the (110) orientation.

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REFERENCES

1. A.Y. Cho and J.R. Arthur, Prog. in Sol. State Chem., **10**, 157 (1975).

2. Thomas P.Pearsall and L.C.R. Thomson, Sol. State Elec., **21**, 297 (1978).

3. J. McKenna and F.K. Reinhart, J. Appl. Phys., **47**, 2069 (1976).

4. H. Kroemer in "Heteroepitaxy on Silicon", J.C.C. Fan and J.M. Poate, eds., Materials Research Society Symposia Proceedings, **67** (Pittsburgh, Pa., 1986), p.3.

5. Chin An Chang, App. Phys. Lett., **40**, 1037 (1982).

6. W.I.Wang, J. Vac. Sci. Technol., **B1**, 630, July-Sept. 1983.

7. J.M. Ballingall and C.E.C. Wood, Appl. Phys. Lett., **41**, 947 (1982).

8. L. Parechanian, E.R. Weber, and T.L. Hierl in "Microscopic Identification of Electronic Defects in Semiconductors", N.M. Johnson et.al., eds., Materials Research Society Symposia Proceedings, **46** (Pittsburgh, Pa., 1985), p.391.

9. L. Parechanian-Allen, E.R. Weber, J. Washburn, and Y.C. Pao, submitted to App. Phys. Lett.

10. Z. Liliental-Weber and L. Parechanian-Allen, App. Phys. Lett., **49**, 1190 (1986).

11. R.D. Brigans, Phys. Rev. Lett., **56**, 520 (1986).

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