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DISCLAIMER

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ABSTRACT

Device quality (110)GaAs has been reproducibly grown by molecular beam epitaxy (MBE) for the first time. Angling of the substrate to expose stable, Ga rich ledges on the (110) surface has been shown to be the necessary condition for two dimensional growth. The epitaxial layers exhibit a room temperature electron mobility of ~5700 cm^2/V-sec for N_{Si}~$4x10^{15}$ and a strong exciton photoluminescence emission at 4K. This breakthrough in MBE growth of III-V compounds allows for fabrication of (110) GaAs devices which will take advantage of the unique properties of this orientation.

INTRODUCTION

GaAs grown by molecular beam epitaxy (MBE) has traditionally been oriented in (100) to take advantage of the natural cleavage planes normal to that crystal face, the smooth morphology of the epitaxial surface obtained with a large range of growth parameters, and the excellent device behavior obtained with that orientation[1]. Layers of high quality (110) epitaxial GaAs grown by MBE are also of importance for many applications, as they promise increased efficiency of, e.g., avalanche devices which depend on ionization impact behavior[2] and optical modulators for integrated optics[3]. In addition, the recent interest of MBE GaAs/Si has made this successful, non-polar (110) GaAs growth a candidate to eliminate the sheet charge resulting from GaAs/Si growth on the polar (100) surface[4,5].

Until this work, all published MBE (110) GaAs/GaAs growths have shown highly defective surfaces with poor optical and electrical device behavior[6-9]. Wood et al. found that the epitaxial behavior of the highly faceted (110) face changed from n-type to p-type above a growth temperature above 550°C. Wang reported a more comprehensive study of (110) GaAs that showed metal droplet formation would cease and n-type behavior maintained if high As overpressure was used but faceting remained. Our previous study had determined the optimal growth parameters of substrate temperature, arsenic overpressure, and growth rate[9] as judged by morphology and optimal electrical and optical behavior.

A careful investigation of the facet geometry with respect to the (110) GaAs crystal surface has shown that they are aligned along [001] with sides composed of (010), (100), and a back (11$\bar{1}$) surface. Each back plane of the facets was composed of a Ga-rich (11$\bar{1}$) polar surface and a kinetic model of facet formation was developed[10]. This examination of facet geometry and initial formation was the key to eliminate faceting of the (110) GaAs surface when grown by MBE. This paper describes experiments which show that, for the first time, repeatably smooth epitaxial layers are obtained when Ga-rich polar ledges are introduced on the (110) GaAs substrate. The experiments support our theory of initial facet formation. The epitaxial layers are examined by variable temperature Hall effect, liquid He photoluminescence (PL), capacitance-voltage (CV) characteristics of Schottky contacts, deep level transient spectroscopy (DLTS), scanning electron microscopy (SEM), and transmission electron microscopy (TEM).

EXPERIMENTAL

The process for MBE growth of GaAs is described elsewhere [1], Optimal growth parameters for the standard Varian GEN II MBE machine equipped with a dual wavelength infrared pyrometer were: substrate temperature of 570°C, arsenic overpressure of As/Ga = 15, and a preferred growth rate of 1.4μ m/hr. The polished substrates were cleaned in a 4: 1: 1 solution of H_2O: H_2O_2: H_2SO_4 before placing them in the MBE loading chamber with In backing on Mo blocks. All growth runs contained a (100) GaAs substrate as a standard, and results are compared to that of the (100) epitaxial film. The epitaxial layers were doped with Si = $5 \times 10^{15}/cm^3$.

Semi-insulating off-axis (110) GaAs substrates were used that were oriented 6° toward (100), 6° toward (010), 6° toward (111), and 6°

toward $(11\bar{1})$ as can be seen on the stereographic projection of Figure 1. The specific orientations were verified by Laue x-ray diffraction. Epitaxial layers of 100Å, 700Å, and 1500Å were grown on each of the four angled substrates and surface morphologies are shown in Figure 2a-2f. Only one out of the four tilting directions resulted in facet free growth. A 1μ m film grown on the successful substrate orientation reproduceded the excellent surface morphology, confirmed with both SEM and TEM investigations.

Convergent beam electron diffraction in the TEM was used to determine the exact polarity of the Ga or As ledges introduced on the substrate of the faceted epitaxial layer as described in [11], utilizing the same convention and stereographic projection as this reference. By symmetry, the ledge nature of the successful substrate is determined.

Figure 3 shows the variable temperature Hall effect plots for the (110) faceted material, (110) non-faceted epitaxial layers and the (100) epitaxial standard. In dots alloyed at 420°C for 20 mins in a N_2 atmosphere provided the ohmic contacts. Doping levels were verified by capacitance-voltage experiments. The electron traps in these layers were characterized by capacitance DLTS, using a double boxcar integrator[12]. For the CV and DLTS measurements, Au-Ge ohmic contacts annealed at 450°C for 40 s and evaporated Au Schottky contacts were obtained by lithography techniques.

Figure 4 shows the PL results for the (110) substrate angled 6° towards $(11\bar{1})$, the (110) epitaxy on the same type of substrate, the epitaxy on (110) substrates, and the (100) epitaxy standard. Each epitaxial layer of Figure 4 was grown under the same MBE conditions. For these measurements, a 5145Å wavelength Ar laser was used at ~25mW to excite the GaAs crystals held at 4K.

RESULTS

The four substrate orientations of Figure 1 introduce ledges approximately every eight atomic layers along the (110) surface. The difference lies in the type of ledge introduced. For the substrates angled 6° toward the (010) and (100), the ledges are nonpolar ones with both Ga and As atoms exposed on the steps. The substrate angled 6° toward (111) exposes polar ledges of all Ga or all As, and the substrate angled 6° towards ($11\bar{1}$) exposes polar ledges opposite in nature, i.e. either all As or all Ga.

For the substrate angled 6° toward (010), Figure 2a shows that faceting occurs by 100Å of epitaxy and the surface continues to facet until the epitaxial layer is replete with faceted sites (Figures 2b, 2c). Figure 2d shows virtually the same results for the substrate angled 6°towards (100) at 1500Å of epitaxial growth. Figure 2e, also a 1500Å film, shows that slightly different morphology is obtained for the epitaxy of the substrate angled 6° toward (111), but faceting is still dominant. There is a startling difference, however, for the epitaxial layer grown on the substrate angled 6° toward ($11\bar{1}$). No faceting is observed for the layers up to 1500Å thick, as shown by the SEM image of Figure 2f. Later films grown on the same type of angled substrate showed no faceting by either SEM or TEM for epitaxial layers $\geq$ 1μm thick.

The careful analysis utilizing the convergent beam diffraction method[11] to determine the As or Ga nature of the substrate ledges yielding faceted growth shows that the angling of the crystal toward (111) (with respect to our standard (110) stereographic projection) yields As rich ledges. This result was confirmed by analysis of the substrates yielding facet free epitaxial growth. The ledges of the latter are Ga rich in nature.

The variable temperature Hall effect of the 1μ m (110) non-faceted epitaxial layer shown in Figure 3 indicate that the carrier concentration as a function of temperature coincided well with the (100) epitaxy behavior. Nearly identical excellent room temperature mobilities of ~5700 cm^2/V-sec are achieved. The carrier mobilities as a function of temperature are also shown in Figure 3. It is clear that the mobility of the non-faceted (110) GaAs is comparable to the (100) standard whereas the mobility of the faceted (110) epitaxy is reduced by ~2 orders of magnitude. The characteristic carrier freezeout with an activation energy of 145 meV has not been found in the non-faceted (110) epitaxial material. Differential analysis of the CV measurements showed that the doping behavior as a function of depth for the non-faceted epitaxial films is uniform and verifies the carrier concentrations shown. DLTS data of the (110) GaAs angled 6° toward $(11\bar{1})$ showed the well known M1, M3, and M5 levels[13] in the 10^{12}-$10^{13}/cm^3$ range, concentrations well comparable with the simultaneously grown (100) GaAs epitaxy.

The PL results of Figure 4 for the faceted (110) material showed a low exciton, neutral acceptor transition (x,A°) peak at 1.512 eV. The dominant neutral carbon acceptor transitions near 1.490 eV indicate a lower quality epitaxy. The PL spectra for the (110) substrate angled 6° toward (11$\bar{1}$)Ga showed a weak bound exciton transition peak (x,D° or A°) as is expected for semi-insulating GaAs. The epitaxy layer grown on the same type of substrate indicated a high quality growth as exhibited by the dominant neutral donor, bound exciton transition (x,D°) peak at 1.514eV as compared with the small neutral carbon acceptor transition (D°,A°) peak at ~1.490eV. PL of the (100) GaAs standard shows comparable luminescence output to the non-faceted (110) GaAs film. These results are indicative of device quality material for both the (100) and non-faceted (110) epitaxial films.

DISCUSSION

The introduction of ledges on a substrate surface can provide preferred sites for initiation of two dimensional growth which is inherent in the MBE process. The above results prove, however, that the nature of the ledges is decisive for growth on the non-polar (110) surface. The introduction of non-polar ledges does not improve the surface morphology over that of the perfect (110) surface. When a Ga and As pair bond to either the (110) surface or the non-polar ledge site to begin to create the next atomic layer, the bonding of the two atoms to the surface naturally exposes both types of {111} planes on the epitaxial layer. With the low sticking coefficient of As, however, the Ga {111} provides the stable growth surface. Facets develop from the fast growing (11$\bar{1}$)Ga surfaces with sides of (100) and (010) that fill in to form the facet shape[10]. Thus, the non-polar ledges obtained when angling the substrate towards either of (100) or (010) still allows the exposure of the stable $(11\bar{1})$Ga facet starting points with the random chemisorbing of Ga and As atomic pairs. The non-polar nature of the ledges does not ensure atomic layer by layer growth of the epitaxial film. Exposure of As rich ledges when angling the substrate 6° towards (111)As has no beneficial result due to the tendency of the As atoms to desorb and leave behind a non-polar ledge and surface once again. Only the exposure of Ga rich ledges, obtained when angling the substrate 6° toward $(11\bar{1})$Ga allows planar growth to proceed. The Ga rich ledges are, therefore, required for facet free growth. The incoming As atoms find four Ga atoms in place on the ledged (110) surface and tend to chemisorb at that favorable ledge site. Thus, the ledge provides a thermodynamically favorable position to begin the next epitaxial layer. Since ledges are maintained throughout the process, two dimensional growth initiates at these ledges for each atomic layer. The MBE growth of the (110) surface is believed to be ensured by the As chemisorption to the available Ga ledges, consistent with the work of Brigans[14].

Excellent electronic and optical behavior for the non-faceted (110) GaAs are exhibited by the Hall effect and PL data. The high electron mobility and the expected doping level show that the amount of self compensation is small and the material is of device quality. The faceted (110) GaAs shows poor electron mobility and strong compensation levels resulting in uncontrollable doping levels[9].

The PL spectrum for the non-faceted epitaxial GaAs, when compared with the faceted GaAs epitaxy of the same growth conditions, indicate that the Si dopant has shifted from predominantly an acceptor site to the donor site on the non-faceted material. This is supported by the shift from a dominant 1.512 eV peak seen in the faceted epitaxial material to that of the (x,D°) peak at 1.514 eV of the non-faceted epitaxial material. Deep levels from DLTS measurements are consistent in type and concentration with the traps commonly observed in (100) GaAs.

CONCLUSION

Device quality GaAs/(110)GaAs by MBE has been reproducibly grown for the first time. Experiments have supported the facet formation model that only exposure of Ga rich ledges leads to a two dimensional MBE growth resulting in a smooth epitaxial material with excellent electrical and optical properties. Only angling the GaAs substrate towards the $(11\bar{1})$Ga results in the exposure of the Ga ledges. The crystalline quality of the epitaxial layer is shown by the high electron mobility in the (110)GaAs when compared with the (100) GaAs standard, the strong neutral donor, exciton luminescence peak of the (110) material, and low deep level concentrations. These results lead the way for investigations of device fabrication as well as fundamental studies which will take advantage of the unique properties of (110) GaAs epitaxial layers.

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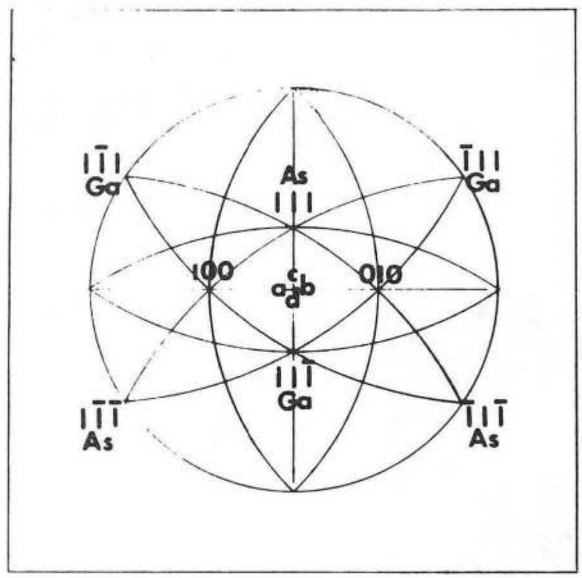
FIGURE CAPTIONS

FIGURE 1. The (110) standard cubic stereographic projection showing the four angled orientations. (a) is 6° towards (100), (b) is 6° towards (010), (c) is 6° towards (111)As, and position (d) is 6° towards $(11\bar{1})$Ga. The projection is of the same sense and polarity as that of [11], and each {111} nature is referenced.

FIGURE 2. SEM images (2600X) of the surface morphology of off-axis GaAs epitaxial layers obtained from angled substrates described in Figure 1.

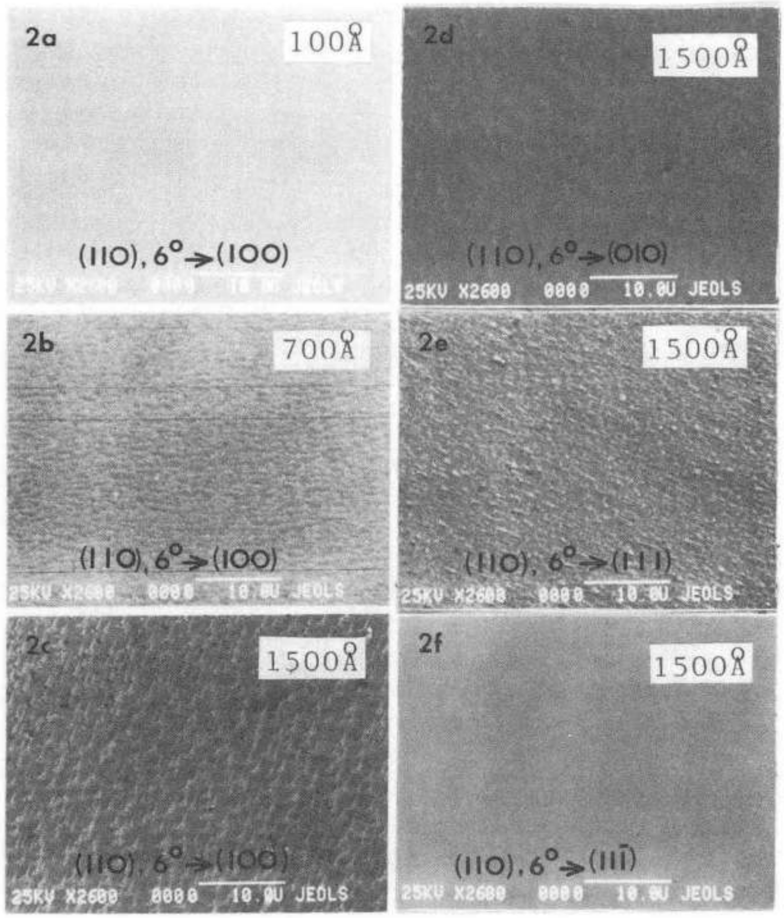
FIGURE 3. Variable temperature Hall effect for (110) non-faceted (110) faceted, and (100) standard GaAs epitaxial material grown by MBE. Free carrier concentration and room temperature electron mobilities are shown as a function of temperature.

FIGURE 4. Liquid He photoluminescence of (100) epilayer standard, (110) substrate angled 6° toward $(11\bar{1})$, (110) faceted epilayer, and (110) non-faceted epilayer.



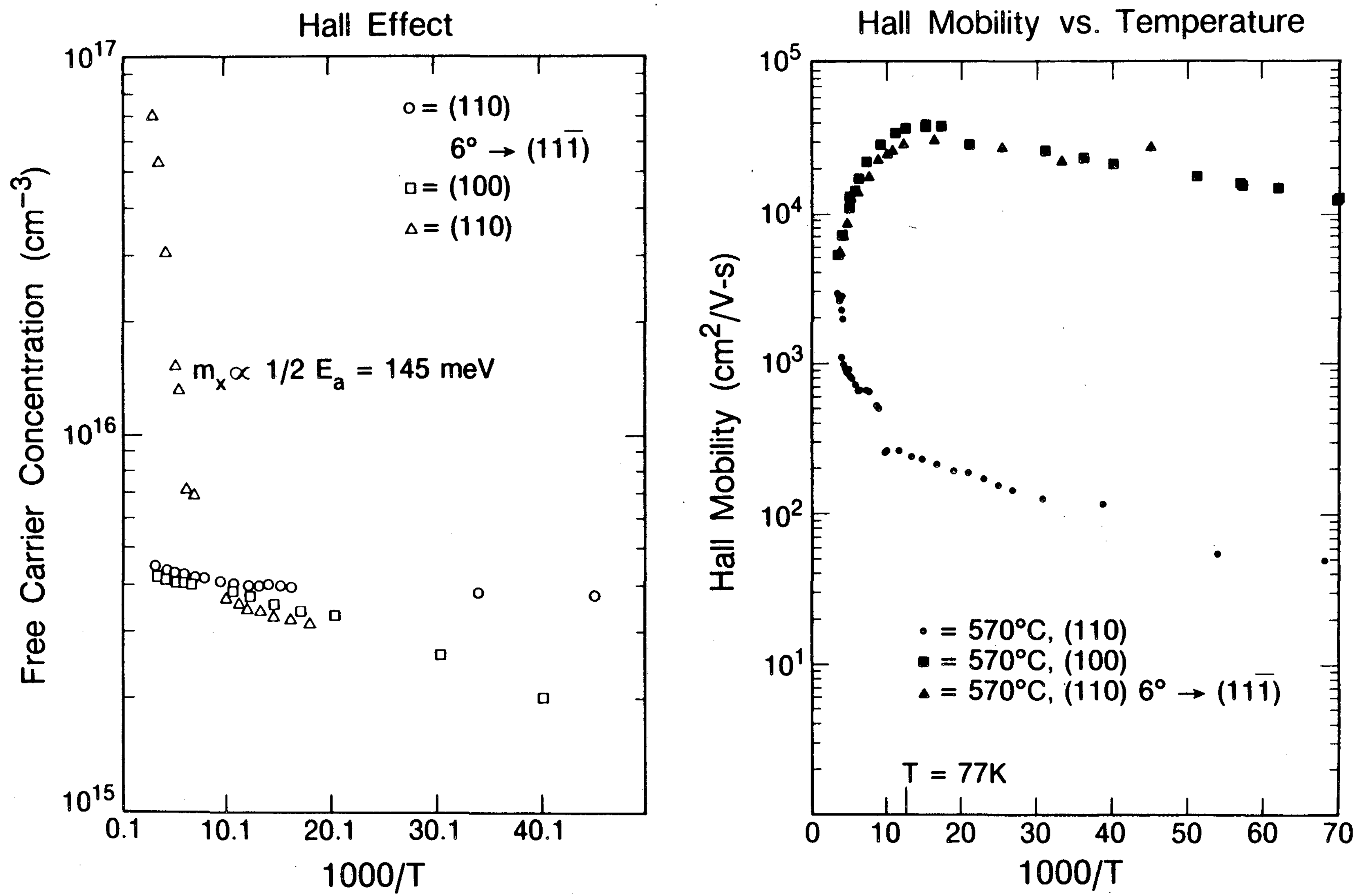
XBL 8611-4617

Fig. 1



XBB 860-8815A

Fig. 2



XBL 8611-4616B

Fig. 3

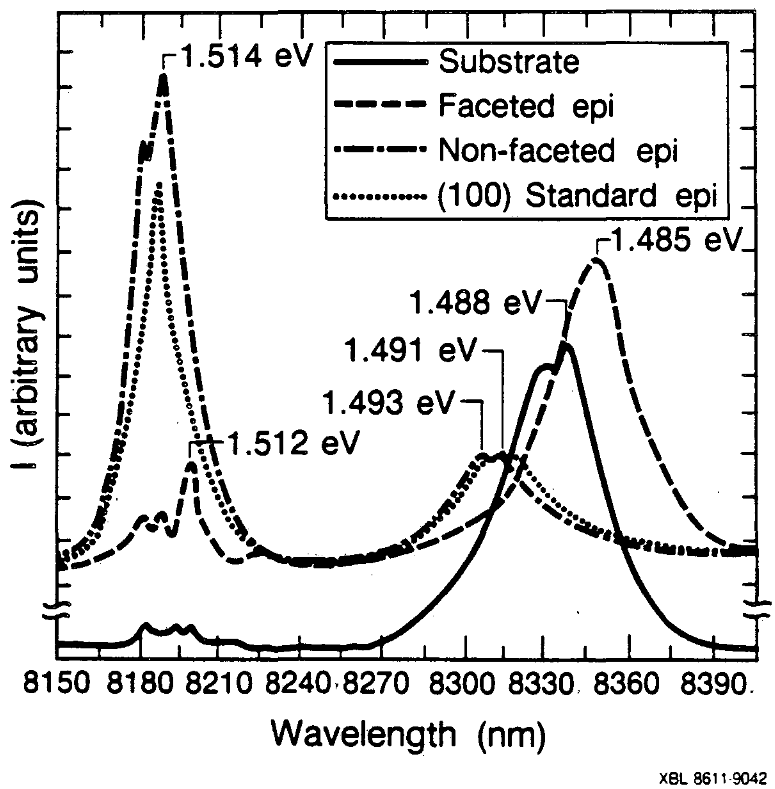

1.514 eV
Substrate
Faceted epi
Non-faceted epi
(100) Standard epi
1.485 eV
1.488 eV
1.491 eV
1.493 eV
1.512 eV
I (arbitrary units)
8150 8180 8210 8240 8270 8300 8330 8360 8390
Wavelength (nm)
XBL 8611-9042

Fig. 4

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