

SLAC-PUB-5367

WISC-EX-92-314

September 1992

(A)

**Electron Spin-Polarization in
Photoemission from Thin $\text{Al}_x\text{Ga}_{1-x}\text{As}^*$**

T. Maruyama and E. L. Garwin

*Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94309*

R. A. Mair and R. Prepost,

Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

J. S. Smith and J. D. Walker

*Department of Electrical Engineering and Computer Sciences, and
The Electronics Research Laboratory, University of California, Berkeley, California 94720*

Submitted to *Journal of Applied Physics*

* This work was supported in part by the U. S. Department of Energy under contract numbers DE-AC03-76SF00515 (SLAC), and DE-AC02-76ER00881 (UW); by the National Science Foundation under contract number NSF-87-11709 (UCB).

ABSTRACT

The polarization of photoemitted electrons from thin $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layers grown by molecular beam epitaxy has been studied as a function of Al concentration by varying x in steps of 0.05 from 0.0 to 0.15. As the fraction x is increased, the wavelength dependence of the polarization shifts toward shorter wavelengths permitting wavelength tuning of the region of maximum polarization. A maximum electron polarization of 42-43% is obtained for $\text{Al}_x\text{Ga}_{1-x}\text{As}$ samples with $x \geq 0.05$ while the maximum polarization of $\text{GaAs}(x=0)$ samples reaches 49%. To investigate the lower polarization of $\text{Al}_x\text{Ga}_{1-x}\text{As}$, additional samples have been studied, including a short-period superlattice $(\text{GaAs})_7-(\text{AlAs})_1$.

Photoemission from negative-electron-affinity (NEA) GaAs has long been used as a source of polarized electrons.^[1] This type of source has many advantages among which are: relative simplicity, high electron yield, and easy reversal of the spin direction. However, there have been two problems in polarized photoemission from GaAs: (1) the maximum measured electron polarization has been about 40-42% whereas the theoretically expected polarization is 50%, (2) the excitation photon wavelength to achieve maximum electron polarization is required to be longer than about 750 nm. The first problem was studied by Alvarado *et al.*^[2] and by Maruyama *et al.*^[3] using molecular beam epitaxy (MBE)-grown thin GaAs layers. These authors observed that the maximum electron polarization depended on the active GaAs layer thickness. Polarization consistent with 50% was observed for samples with GaAs layer thicknesses less than 0.4 μm and an excitation photon wavelength longer than about 760 nm. More recently much effort has been devoted to achieving polarization much higher than 50% by removing the valence band degeneracy at the Γ point of the III-V compounds. Polarization in excess of 70% was observed from a strained InGaAs layer grown on a GaAs substrate,^[4] and subsequently polarization as high as 90% was achieved using strained GaAs grown on GaAsP.^[5] Polarization enhancements were also observed in GaAs-AlGaAs superlattice structures.^[6] However, photoemission quantum efficiencies of these high polarization materials are typically less than 0.1%, and further developments are required to utilize these materials for polarized electron sources.

The second problem is of a more practical nature. If high peak electron currents are not required, lasers in the appropriate wavelength region are available (e.g. AlGaAs diode lasers). However in a situation where high peak currents are

required, the choice of lasers is limited. The polarized electron source for the Stanford Linear Collider (SLC)^[7] must deliver in excess of 10^{11} electrons in a 2 nsec pulse at 120 pps, corresponding to a peak current as high as 8 A. These conditions require an excitation laser pulse with a peak power of more than 50 kW. Such a high peak power laser with a wavelength of ~ 760 nm and a 120 pps repetition rate is not readily available, and a flash lamp pumped dye laser is one of the few available options. Based on studies of laser dyes, it was found that the laser dyes in the infra-red wavelength region have short active lifetimes.^[8] For example, the dye LD700 lasing at $\lambda = 740$ nm, degraded in output power with a lifetime of 41 hours when operated at 60 pps, whereas the dye Oxazine 720 lasing at $\lambda = 700-710$ nm had a lifetime of about 200 hours. Since the accelerator must be operated without any interruptions for many days, it is highly desirable to be able to operate the laser using Oxazine 720. However, the polarization obtained with this wavelength is only about 30% since the appropriate wavelength to saturate the polarization near 50% requires a wavelength in excess of 760 nm^[3]. If the polarization wavelength dependence were to be shifted about 50 nm towards a shorter wavelength, a maximum polarization near 50% could in principle be achieved with a flash lamp pumped dye laser using Oxazine 720.

There are two ways to achieve a wavelength shift: (1) cool the GaAs crystal to liquid nitrogen temperature, thus increasing the band gap to 1.51 eV from 1.42 eV at room temperature; (2) add about 10% of aluminum or phosphorus to GaAs. Although method (1) is relatively simple, the cathode quantum efficiency decreases rapidly because the residual gases, particularly carbon-dioxide and carbon monoxide are adsorbed on the cold GaAs surface.^[9] In the present study, method (2) was

used. Studies of polarized electron sources using the III-V bulk alloys AlGaAs and GaAsP have been reported previously, showing spin-polarizations of 35-45%.^[10] The present work attempts to achieve 50% polarization using MBE-grown thin AlGaAs layers.

For the present experiment, thin $\text{Al}_x\text{Ga}_{1-x}\text{As}$ samples were grown by MBE at the University of California in Berkeley. A schematic diagram of the sample structure is shown in Fig. 1. The substrate material used was (100) *n*-type (Si doped to $5 \times 10^{18} \text{ cm}^{-3}$) GaAs. Since heavy *p*-type doping is necessary to achieve a NEA surface, a tunnel junction was formed in the buffer layer in order to change the carrier type by depositing a $0.4 \mu\text{m}$ thick *n*-type GaAs (Si doped to $5 \times 10^{17} \text{ cm}^{-3}$) followed by a $0.2 \mu\text{m}$ thick *p*-type GaAs (Be doped to $5 \times 10^{17} \text{ cm}^{-3}$). Then, a $0.9 \mu\text{m}$ thick layer of *p*-type $\text{Al}_{0.45}\text{Ga}_{0.55}\text{As}$ (Be doped to $5 \times 10^{18} \text{ cm}^{-3}$) was grown, followed by the active layer of *p*-type $\text{Al}_x\text{Ga}_{1-x}\text{As}$ (Be doped to $5 \times 10^{18} \text{ cm}^{-3}$). The $\text{Al}_{0.45}\text{Ga}_{0.55}\text{As}$ intermediate layer serves as a potential barrier to isolate the active $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer from the substrate GaAs. Three different samples were grown with nominal aluminum concentrations of $x=0.05$, 0.10 , and 0.15 , as well as a GaAs($x=0$) reference sample. The active layer thickness of all the samples was $0.3 \mu\text{m}$. A thin GaAs layer was grown on top of the active $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer to prevent oxidation of aluminum in the active layer.^[11] The thickness of the cap GaAs layer was 50 \AA for the $x=0.05$ and $x=0.10$ samples, and 100 \AA for the $x=0.15$ sample. After the MBE growth, the sample was cooled to below room temperature in about 3 hours and was then exposed to an arsenic beam for 10 minutes to deposit a protective cap layer.^[12]

Photoluminescence measurements were performed to determine the aluminum

concentration of the samples. The measurements were made at room temperature using a HeNe laser (633 nm) and a diode laser with wavelength 750 nm. As a cross check, the nominal $x=0.15$ sample was also analyzed with a double-crystal X-ray diffractometer using the (004) Bragg reflection of the CuK_α radiation. The relation $E(x)=E(0) + 1.455x$ was used to determine the value of x from the photoluminescence data.^[13] Here $E(0)$ and $E(x)$ are the measured photoluminescence peak energies (eV) corresponding to $x=0$ and x respectively. Using the measured $E(0)=1.43$ eV, the resulting values of x were $x=0.068$, 0.106 , and 0.144 , for the nominal $x=0.05$, 0.10 , and 0.15 samples respectively. The aluminum fraction for the nominal $x=0.15$ sample, measured using X-ray diffraction, was determined to be $x=0.148$, consistent with the photoluminescence measurement.

The electron spin-polarization was measured at room temperature by Mott scattering at 65 keV. The electron gun and Mott scattering apparatus have been described elsewhere.^[14] Cesium and nitrogen-trifluoride were used to obtain a NEA surface. The arsenic cap layer was removed during a heat treatment (600°C for 1 hour) prior to the first cathode activation. A dye laser, pumped by a nitrogen laser, was used as the photoexcitation source. Circularly polarized light was produced by a linear polarizer and a Babinet-Soleil compensator. A more detailed description of the experimental setup may be found in Ref. 3.

Fig. 2(a) shows the measured photoelectric quantum efficiencies (Q.E.) as a function of the photon wavelength for the three $\text{Al}_x\text{Ga}_{1-x}\text{As}$ samples and the $\text{GaAs}(x=0)$ reference sample. The band gap energies for each sample obtained from photoluminescence measurements are also indicated in the figure. The rollover near the band gap of the $x=0.10$ and 0.15 samples is due to photoemission from the

GaAs cap layer. As expected, the quantum efficiency curve shifts towards shorter wavelength with increasing aluminum concentration in accord with the increase in band gap energy.

Fig. 2(b) shows the electron polarization as a function of excitation photon wavelength measured within five hours after cathode activation.^[15] The measurements for the GaAs($x=0$) reference sample are also shown in the figure. The wavelength dependence of the polarization is seen to shift towards shorter wavelength as the aluminum concentration is increased. However, the maximum electron polarization is 42-43% for all three aluminum concentrations and never reaches the level observed for the thin GaAs sample. The sharp polarization increase near the band gap observed by F. Ciccacci *et al.* for AlGaAs^[16] is not seen in the present experiment. Since the Q.E. decreases for longer wavelengths, the optimum operating wavelength is where the maximum electron polarization is reached from the shorter wavelength side. For the laser wavelengths of 700-710 nm obtained with Oxazine 720, the required aluminum concentration is about 13%.

In order to investigate the effect of Al concentration on spin depolarization, sample characteristics were changed and additional samples were studied. (1) In order to study oxidation of the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ surface, the $x=0.15$ sample was grown with the GaAs cap layer increased from 50 Å to 100 Å. No change of the maximum polarization was observed, as shown in Fig. 2(b). (2) For the 100 Å cap layer of an additional $x=0.10$ sample, the first 50 Å (nearest the active layer) was graded from $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with $x=0.10$ to $x=0.0$. This procedure was used to remove any possible band discontinuities in the conduction bands of the active $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and the cap GaAs layers. Such a band discontinuity might be responsible for electron

scatterings and consequent spin-depolarizations. No change of the maximum polarization was observed (not shown in the Figures). (3) Two 0.3 μm thick GaAs ($x=0.0$) samples were made to check for any systematic problems in the MBE as well as the Mott polarimeter. Fig. 3 shows the results of the measurements for the two 0.3 μm GaAs samples: one sample was grown and the polarization measured (solid circles) before the growth and measurement of the AlGaAs samples (the same data are shown in Fig. 2 (b)), while another sample was independently grown and the polarization measured (open circles) after the AlGaAs measurements were completed. The measurements were reproducible, and a maximum polarization of 49% was also observed. (4) A sample was prepared with the active region aluminum concentration reduced to $x=0.01$. As seen in Fig. 3, a maximum polarization of 49% was observed. (5) To study the effect of alloy scattering of photoexcited electrons in $\text{Al}_x\text{Ga}_{1-x}\text{As}$, a superlattice structure of $(\text{GaAs})_7-(\text{AlAs})_1$ with an effective aluminum fraction $x=0.125$ was grown using phase-locked epitaxy.^[17] As shown in Fig. 3, although the maximum polarization reached 46% near the band gap, the plateau polarization was 42.5%. The polarization increase near the band gap may very well be associated with the valence band splitting expected for the superlattice structure of this sample. From these studies, it was concluded that the spin depolarization effect seen in the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ samples with nominal $x=0.05, 0.10$ and 0.15 values was associated with the aluminum in the samples.

In conclusion, the polarization of photoemitted electrons from MBE grown thin AlGaAs layers has been measured as a function of aluminum concentration in AlGaAs. By increasing the aluminum concentration, the wavelength dependence of the polarization shifts towards shorter wavelengths. However, the observed

maximum polarization is 42-43% compared to the near 50% level observed in comparably thin GaAs($x=0$) samples. This spin-depolarization effect is believed to be associated with the aluminum in AlGaAs, but the mechanism is unknown.

We would like to thank E. D. Commins of the University of California, L. W. Anderson and J. E. Lawler of the University of Wisconsin for the loan of lasers, and G. Collet for his skillful technical assistance. We would also like to thank F. Perrier for performing the dye lifetime tests. This work was supported in part by the U. S. Department of Energy under contract numbers DE-AC03-76SF00515 (SLAC), and DE-AC02-76ER00881 (UW); by the National Science Foundation under contract number NSF-87-11709 (UCB).

REFERENCES

1. See for example, J. Kessler, *Polarized Electrons*, 2nd ed. (Springer, Berlin, 1985), and J. Kirschner, *Polarized Electrons at Surfaces*, (Springer, Berlin, 1985).
2. S. F. Alvarado, F. Ciccacci, S. Valeri, M. Campagna, F. Feder, and H. Pleyer, *Z. Phys.* B44, 259 (1981).
3. T. Maruyama, R. Prepost, E. L. Garwin, C. K. Sinclair, B. Dunham, and S. Kalem, *Appl. Phys. Lett.* 55(16), 1686 (1989).
4. T. Maruyama, E. L. Garwin, R. Prepost, G. H. Zapalac, J. S. Smith, and J. D. Walker, *Phys. Rev. Lett.* 66, 2376 (1991).
5. T. Maruyama, E. L. Garwin, R. Prepost, and G. H. Zapalac, *Phys. Rev.* B46, 4261 (1992); T. Nakanishi *et al.*, *Phys. Lett.* A158, 345 (1991); H. Aoyagi *et al.*, *Phys. Lett.* A167, 415 (1992).
6. T. Omori *et al.*, *Phys. Rev. Lett.* 67, 3299 (1991), and Y. Kurihara *et al.*, *Nucl. Instrum. Methods*, A313, 393 (1992).
7. J. E. Clendenin, in *Proceedings of the 9th International Symposium on High Energy Spin Physics*, edited by W. Meyer, E. Steffens, and W. Thiel (Springer-Verlag, Berlin, 1991), Vol. 2, p. 3.
8. K. C. Moffeit, in *Proceedings of the 8th International Symposium on High Energy Spin Physics*, edited by K. J. Heller (American Institute of Physics, New York, 1989), p. 901. The laser used for the test is a flash-lamp-pumped dye laser manufactured by Candella Laser Co., Wayland, MA, and the dyes

used for the tests are from Exiton Chemical Co., Dayton, OH.

9. The polarized electron source described in C. Prescott *et al.*, Phys. Lett. 77B, 347 (1978) was operated with a GaAs cathode at about 90°K. The average polarization of 37% was achieved using the Oxazine 720 dye, but the cathode lifetime was about 10 hours.
10. D. Conrath, T. Heindorff, A. Hermanni, N. Ludwig, and E. Reichert, Appl. Phys. 20, 155 (1979), F. Ciccacci, S. F. Alvarado, and S. Valeri, J. Appl. Phys. 53(6), 4395 (1982), J. Kirschner, H. P. Oepen, and H. Ibach, Appl. Phys. A30, 177 (1983), F. Ciccacci, H.-J. Drouhin, C. Hermann, R. Houdre, and G. Lampel, Appl. Phys. Lett. 54(7), 632 (1989), W. Hartmann *et al.*, Nucl. Instrm, and Methods A286, 1 (1990)
11. F. Ciccacci, H.-J. Drouhin, C. Hermann, R. Houdre, and G. Lampel, Appl. Phys. Lett. 54(7), 632 (1989).
12. For the details of arsenic capping, see D. L. Miller, R. T. Chen, K. Elliott, and S. P. Kowalczyk, J. Appl. Phys. 57(6), 1922 (1985).
13. T. F. Kuech *et al.*, Appl. Phys. Lett. 51, 505 (1987).
14. C. K. Sinclair, E. L. Garwin, R. H. Miller, and C. Y. Prescott, in "Proceedings of the Argonne Symposium on High Energy Physics with Polarized Beams and Targets", edited by M. L. Marshak (American Institute of Physics, New York, 1976), p. 424.
15. Since the polarization increases as the cathode ages, all measurements were made within five hours after activation.
16. F. Ciccacci, S. F. Alvarado, and S. Valeri, J. Appl. Phys. 53(6), 4395 (1982).

17. J. D. Walker, K. Malloy, S. Wang, and J. S. Smith, *Appl. Phys. Lett.* 56(25), 2493 (1990).

FIGURE CAPTIONS

Fig. 1 Schematic diagram of the sample structure.

Fig. 2 (a) Cathode quantum efficiency as a function of excitation photon wavelength for the AlGaAs and GaAs samples. The band gap energies of the samples measured by photoluminescence are indicated. (b) Electron spin-polarization as a function of excitation photon wavelength for the AlGaAs and GaAs samples. The solid curves are drawn to guide the eye.

Fig. 3 Electron spin-polarization as a function of excitation photon wavelength for some of the additional samples grown to investigate possible depolarization effects of AlGaAs: the two GaAs samples (solid and open circles), the $x=0.01$ AlGaAs sample (square), and the $(\text{GaAs})_7\text{-(AlAs)}_1$ superlattice (triangle).

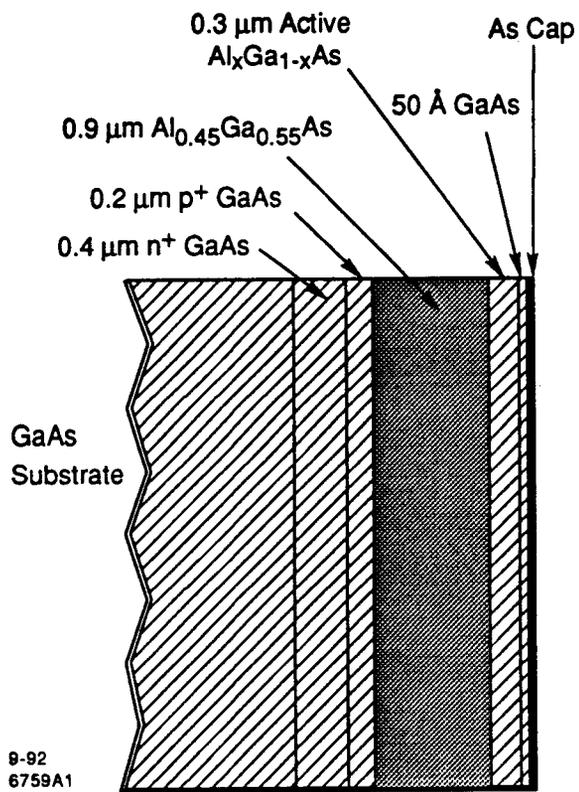
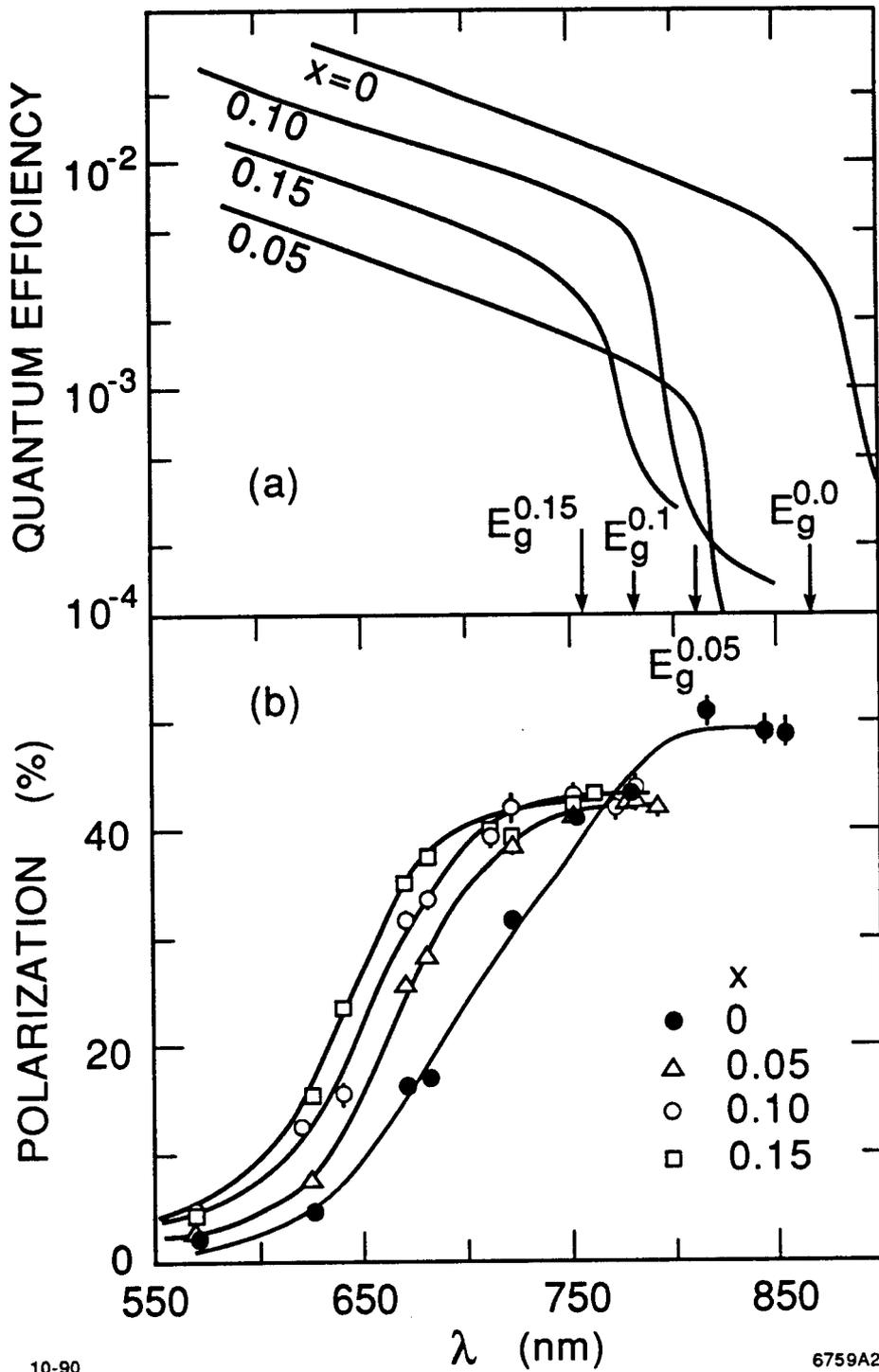


Fig. 1



10-90

6759A2

Fig. 2

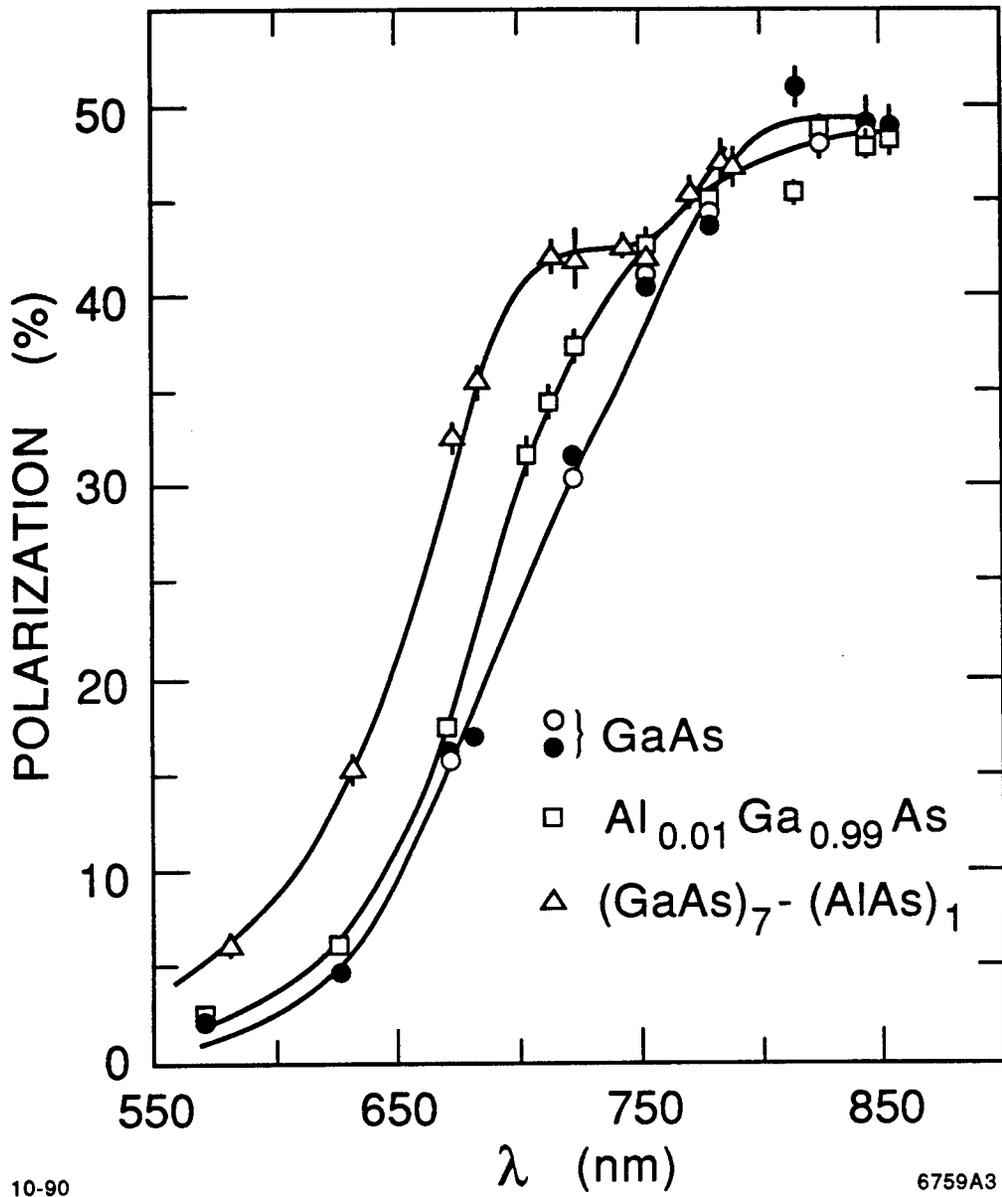


Fig. 3