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Enhanced Electron Spin-Polarization in Photoemission from Thin GaAs*

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ABSTRACT

The polarization of photoemitted electrons from thin GaAs layers grown by molecular beam epitaxy(MBE) has been measured. Polarization as high as 49% was observed for a 0.2 μm thick GaAs sample at excitation photon wavelengths longer than 750 nm. The maximum polarization is dependent on the thickness of the GaAs layer, decreasing to about 41% for a 0.9 μm thick GaAs sample.

Electron positron collisions at high energy are very important for studying the electroweak interaction. Since the weak interaction distinguishes between left and right handed fermions, left and right handed electrons interact with positrons in a fundamentally different way and there is an important role for experiments with longitudinally polarized electrons. Accelerators such as the Stanford Linear Collider(SLC) will utilize a polarized electron source capable of providing the high peak current pulses suitable for injection into the accelerator. Although there are several types of polarized electron sources available,[1] photoemission from a negative-electron-affinity (NEA) photocathode is presently the only type of source which meets the high peak current requirements. This type of source was used quite successfully in the SLAC polarized e-D scattering experiment providing in excess of 5×10^{11} electrons in a 1.6μsec long pulse with an average spin-polarization of 37%.[2] This type of source also has the advantage that the electron spin can be readily reversed by reversing the circular polarization of the excitation photons.

Although the electron polarization from NEA GaAs is theoretically expected to reach 50%, the maximum measured polarization has been about 42%. There have been many theoretical and experimental investigations to understand this spin relaxation effect.[3] Using a MBE grown GaAs layer with thickness 0.24 μm, Alvarado *et al.* observed a maximum spin-polarization of 49%,[4] indicating that the reduced polarization in thick samples is due to the spin relaxation of the photo-excited electrons drifting towards the GaAs surface before escaping into the vacuum. The present experiment has been performed to confirm this observation by systematically varying the thickness of the GaAs layer. In addition, a barrier layer of AlGaAs was used to prevent photocurrent contributions from the GaAs substrate.

Thin GaAs samples were grown by the MBE technique at the Coordinated Science Laboratory of the University of Illinois. A schematic diagram of the sample structure is shown in Fig. 1. Prior to the MBE growth, the (100) GaAs substrate (Zn doped to 5×10^{18} cm^{-3}) was cleaned in an etching solution of 5:1:1 sulfuric acid, hydrogen peroxide, and water. First, a 0.2 μm thick buffer layer of p-type GaAs (Be doped to 5×10^{18} cm^{-3}) was grown on the substrate held at 580°C, followed by a 0.9 μm thick layer of p-type $Al_{.3}Ga_{.7}As$ (Be doped to 5×10^{18} cm^{-3}) at 610°C. Then, the active layer of p-type GaAs (Be doped to 5×10^{18} cm^{-3}) was grown at 580°C. The heavy p-type doping is a necessary condition for later achieving a NEA surface. Since the photon absorption length inside GaAs is about 1 μm, four different samples were grown with active GaAs layer thicknesses of 0.2, 0.425, 0.7, and 0.9 μm. After the MBE growth, the samples were capped with a 200 Å layer of antimony for protection,[5] and were then stored in dry nitrogen gas. The $Al_{.3}Ga_{.7}As$ intermediate layer serves as a barrier to isolate the active GaAs layer from the substrate GaAs; namely upon photon excitation with energy smaller than the $Al_{.3}Ga_{.7}As$ bandgap (E_g=1.86 eV), electrons produced in the GaAs substrate will not penetrate this barrier into the active GaAs. Only electrons produced in the active GaAs are then photoemitted into the vacuum so that the spin-relaxation effect can then be investigated as a function of the active GaAs thickness.

The electron spin-polarization was measured by Mott scattering at 65 keV. The electron gun and Mott scattering apparatus have been described elsewhere.[6] A nitrogen laser pumped dye laser, using various dyes to obtain the desired wavelength range, was used as the photoexcitation source.[7] Circularly polarized light was produced by a linear polarizer and a Babinet-Soleil compensator. Prior to installation in the gun cathode, each GaAs sample was degreased sequentially in boiling solutions of trichloroethylene, ethanol, and methanol. After the sample was installed and the chamber evacuated, the gun was baked at 250°C for about 40 hours and at 150°C for 24 hours to achieve the necessary ultrahigh vacuum. During the bake, the GaAs cathode was maintained at about 280°C by electron bombardment of the back of the cathode support structure. The final pressure during the subsequent polarization measurements was in the low 10^{-10} Torr range.

Cesium and nitrogen-trifluoride were used to obtain a NEA surface. Although cesium and oxygen are commonly used for NEA activation, nitrogen-trifluoride has been found to give a higher quantum yield and more stable photocurrent than oxygen.[8] The antimony cap layer was removed during a heat cleaning process (600°C for 1 hour) before the first activation. The photocurrent decreased rapidly for the initial two activations with a lifetime[9] less than about 20 hours. At least three activations were typically required to obtain stable photocurrents with lifetimes as long as 500 hours.

The photoelectric quantum efficiencies were measured using two methods. A 2.6 mW HeNe laser was used to measure the absolute quantum efficiency at a photon wavelength of 632.8 nm. A xenon flash lamp and a monochrometer, whose output was monitored by a photodiode, were used to measure the relative quantum efficiency as a function of photon wavelength, and these measurements were then normalized to the HeNe laser measurement at 632.8 nm. Although the gun assembly had the capability for cooling the cathode to liquid nitrogen temperature, the present measurements were made with the cathode at room temperature.[10]

Fig. 2 shows the measured electron polarization as a function of photon wavelength for the 0.2 μm GaAs sample. The electron polarization was also measured as a function of time to investigate the cathode aging effect. Three sets of measurements are shown in the figure; within 5 hours after the activation, one day, and four days later. Electron polarizations as high as 49% were observed at wavelengths longer than about 750 nm. The error bars shown in the figure represent the statistical error only. The cathode activation and the polarization measurement were each repeated several times, and the polarizations were found to be reproducible. For the particular activation shown in the figure, the photocurrent decreased with a lifetime of about 80 hours for the first 1.5 days and then stabilized with a lifetime of about 400 hours. The data show a systematic increase in the electron polarization below $\lambda \approx 750$ nm during the initial decay period. This is due to the fact that photoemitted electrons with lower energy in the conduction band undergo more spin-depolarizing interactions, but are less likely to contribute to the photocurrent as time passes since the surface electron affinity is increasing with time. This has the effect of shifting the polarization versus wavelength curve toward shorter wavelength. Once the photocurrent decay rate decreased, the electron polarization became stable. A similar polarization increase associated with cathode aging has been reported.[11] The dashed curve in Fig. 2 represents the quantum efficiency as a function of photon wavelength, measured immediately after cathode activation. The quantum efficiency decreases as the wavelength increases. The quantum efficiency at λ=750 nm, where the maximum spin-polarization is reached, is about 1%.

The polarization and quantum efficiency measurements were repeated for the other GaAs samples. Fig. 3 shows the electron spin-polarization as a function of excitation photon wavelength for all four GaAs samples. In consideration of the cathode aging effect described above, all the measurements shown in the figure were made within five hours after cathode activation. For wavelengths longer than about 760 nm the electron polarization depends strongly on the GaAs thickness, decreasing from 49% for the 0.2 μm sample to about 41% for the 0.9 μm sample. The results are consistent with the hypothesis that spin relaxation is occuring while electrons are drifting towards the surface, and that the effect of spin relaxation can be reduced by limiting the electron drift distance. The data for the 0.2 μm sample are in good agreement with the results of Alvarado *et al.*[4] The data for the 0.9 μm sample are consistent with the data for bulk GaAs samples measured with the present apparatus, and with other published data.[12]

There is a systematic uncertainty in the absolute polarization measured by Mott scattering. The present polarized electron gun and Mott polarimeter were previously used for the SLAC inelastic electron scattering experiment which observed a parity violating asymmetry.[2] During that experiment, the electron polarization was measured regularly by high energy elastic electron-electron scattering (Møller scattering) and compared to the polarization measurements using the Mott apparatus. From this comparison, the average ratio of Møller to Mott polarization was found to be 0.979 ± 0.011.[13] Since this experiment, electron polarization measurements have been made frequently with the Mott apparatus and no indications of calibration drift have been found. The systematic uncertainty of the present measurements is thus estimated to be $\delta P_{e^-}/P_{e^-} = \pm 0.05$, which is the estimated systematic uncertainty of the Møller polarimeter.

Table 1 shows the quantum efficiencies of the samples measured at the HeNe laser wavelength of 632.8 nm, and at the time of the polarization measurement. The numbers in parentheses indicate the maximum observed quantum efficiency for each sample but not necessarily at the same activation when the polarization was measured. There is no significant observed correlation between the quantum efficiency and the thickness of the surface GaAs layer. This is not surprising for variable GaAs surface conditions. The quantum efficiency for an NEA cathode can be expressed by

$$Q.E. = \frac{P_{esc}}{1+(\alpha L)^{-1}} \cdot \left[1 - e^{-(1+\alpha L)(t/L)}\right],$$

where P_{esc} is the surface escape probability, α^{-1} the light absorption length, L the electron diffusion length, and t the thickness of the GaAs active layer. Since α^{-1} is about 0.5 μm at 632.8 nm and L is between 2 and 5 μm for MBE grown GaAs, the quantum efficiency is expected to vary systematically with thickness by as much as a factor of three for a constant P_{esc}. The scatter in the results for the quantum efficiency indicates that in the present case the determining factor for the quantum efficiency is a variable surface escape probability. This parameter is critically dependent on the surface conditions of the MBE growth, the cleanliness of the GaAs surface remaining after heat treatment removal of the Sb cap layer, and the cathode activations.

In conclusion, the polarization of photoemitted electrons from thin GaAs layers has been measured as a function of the GaAs layer thickness. Polarization as high as 49% with a quantum efficiency of about 1% was observed for the 0.2 μm thick sample. The maximum polarization is dependent on the GaAs layer thickness, decreasing to about 41% for the 0.9 μm sample.

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2. C. Y. Prescott *et al.*, Phys. Lett. 77B, 347 (1978), and Phys. Lett. 84B, 524 (1979).

3. G. Fishman and G. Lampel, Phys. Rev. B16, 820 (1977), A. G. Aronov *et al.*, Sov. Phys. JETP, 57, 680 (1983), and H. J. Drouhin *et al.*, Phy. Rev. B31, 3859, and 3872 (1985).

4. S. F. Alvarado *et al.*, Z. Phys., B44, 259 (1981).

5. For the details of antimony capping, see T. M. Kerr *et al.*, J. Appl. Phys., 63, 1494 (1988).

6. 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.

7. The following dyes were used:
   HITC(840nm), HITC+DOTC(820nm), DOTC(775nm),
   Oxazine 750(750nm), LD700(720nm), Oxazine 720(670 nm),
   Rhodamine 640(625nm), and Rhodamine 590(575nm). The numbers in parenthesis indicate the wavelength at the maximum lasing intensity.

8. C. K. Sinclair, in "Proceedings of the Symposium on Advanced Accelerator Concepts", AIP Conference Proceedings 156, edited by F. E. Mills (American Institute of Physics, New York, 1987), p.298.

9. The lifetime is defined to be the time required for the photocurrent to decrease by a factor of e although the photocurrent does not always decrease exponentially.

10. The band gap increases at lower temperature and therefore the polarization vs. wavelength curve shown in Fig. 2 would shift towards a shorter wavelength. However, a cold cathode would condense residual gases, and the quantum yield would decrease more rapidly with time than for a cathode at room temperature.

11. For example, H. J. Drouhin *et al.* in Ref. 3.

12. D. T. Pierce *et al.*, Phys. Lett. 51A, 465 (1975), and D. T. Pierce and F. Meier, Phys. Rev. B13, 5484 (1976).

13. T. Maruyama and C. Y. Prescott, SLAC-SLCPOL Note 25, March 1989.

Table 1. Quantum efficiencies at a wavelength of 632.8nm.

The numbers in parentheses indicate the maximum observed quantum efficiency but not necessarily at the same activation when the polarization was measured.

GaAs thickness	Q.E. (%)	
0.2	1.8	(1.8)
0.425	0.5	(0.5)
0.7	0.4	(1.5)
0.9	0.5	(2.6)

FIGURE CAPTIONS

Fig. 1 Schematic diagram of the sample structure.

Fig. 2 Electron polarization as a function of excitation photon wavelength for the 0.2 μm thick GaAs sample measured within five hours after activation(closed circles), after one day(open circles), and after four days(triangles). The dashed curve shows the quantum efficiency as a function of wavelength.

Fig. 3 Electron spin-polarization as a function of excitation photon wavelength for four different thicknesses of GaAs samples. All the measurements were made within 5 hours after cathode activation.

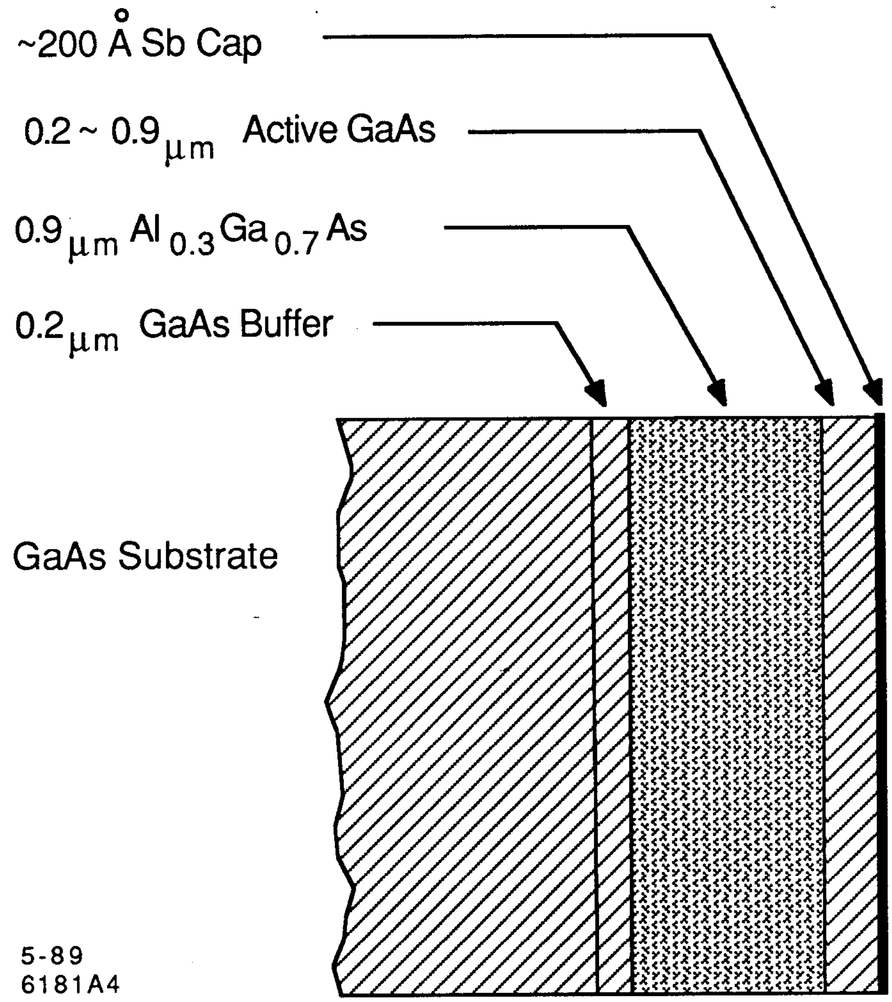

~200 Å Sb Cap
0.2 ~ 0.9 μm Active GaAs
0.9 μm Al 0.3 Ga 0.7 As
0.2 μm GaAs Buffer
GaAs Substrate
5-89
6181A4

Fig. 1

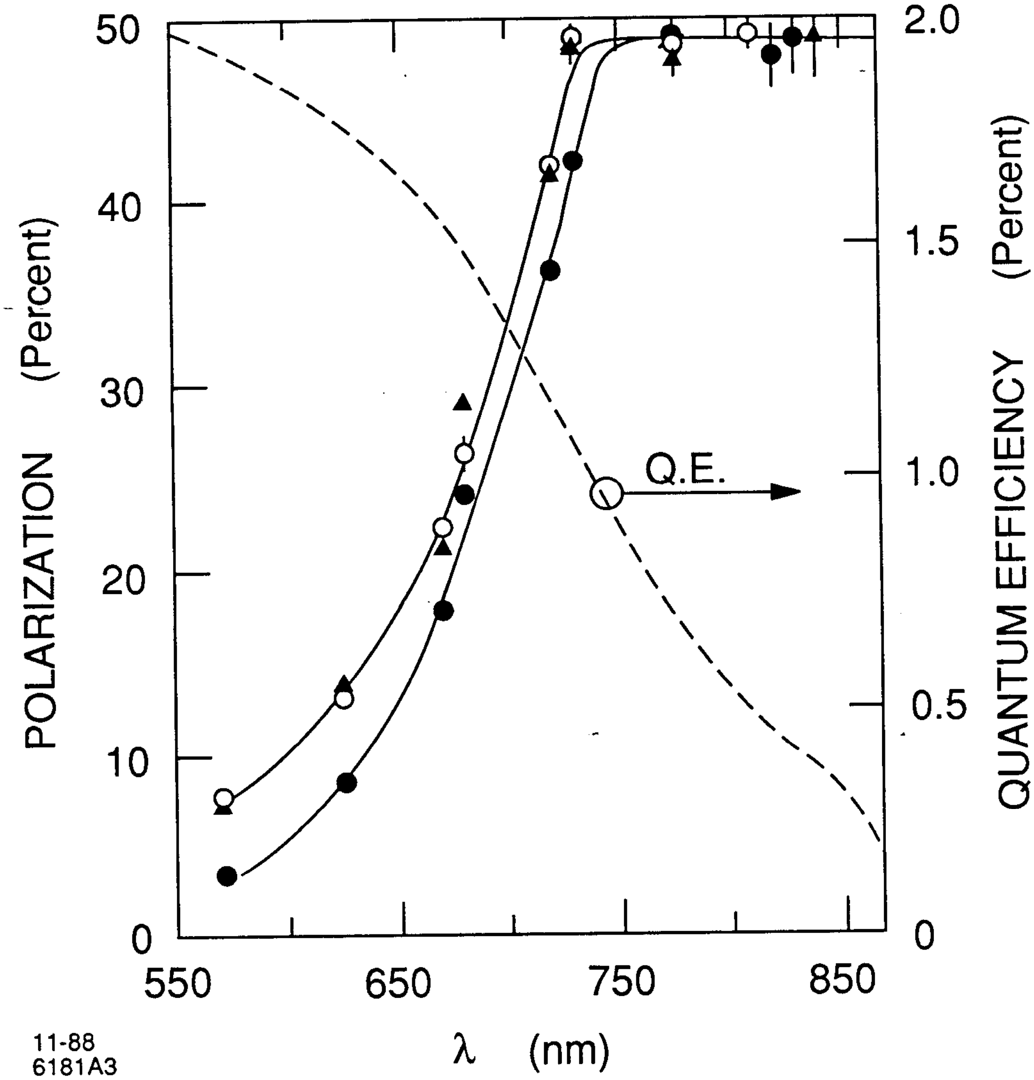
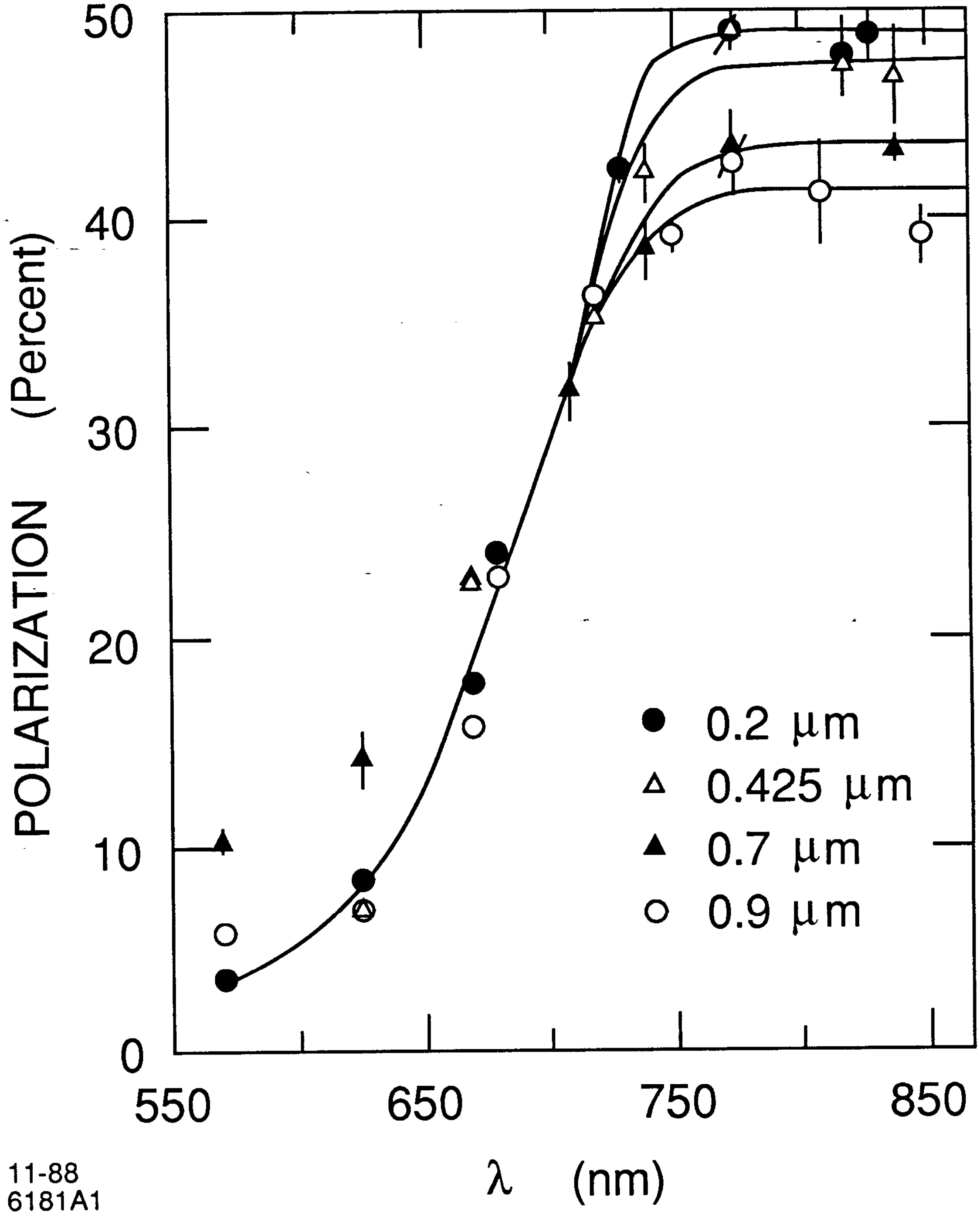

50
40
30
20
10
0
POLARIZATION (Percent)
2.0
1.5
1.0
0.5
0
QUANTUM EFFICIENCY (Percent)
Q.E.
550
650
750
850
λ (nm)
11-88
6181A3

Fig. 2



50
40
30
20
10
0
550
650
750
850
POLARIZATION (Percent)
λ (nm)
0.2 µm
0.425 µm
0.7 µm
0.9 µm
11-88
6181A1

Fig. 3