Electron-spin polarization in photoemission from thin $Al_xGa_{1-x}As$

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

The polarization of photoemitted electrons from thin $Al_xGa_{1-x}As$ 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 $Al_xGa_{1-x}As$ samples with $x \geqslant 0.05$ while the maximum polarization of GaAs ($x=0$) samples reaches 49%. To investigate the lower polarization of $Al_xGa_{1-x}As$, additional samples have been studied, including a short-period superlattice $(GaAs)_7$-$(AlAs)_1$.

I. INTRODUCTION

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 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-ns 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 infrared 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 h when operated at 60 pps, whereas the dye Oxazine 720 lasing at $\lambda = 700$–710 nm had a lifetime of about 200 h. 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 toward 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.
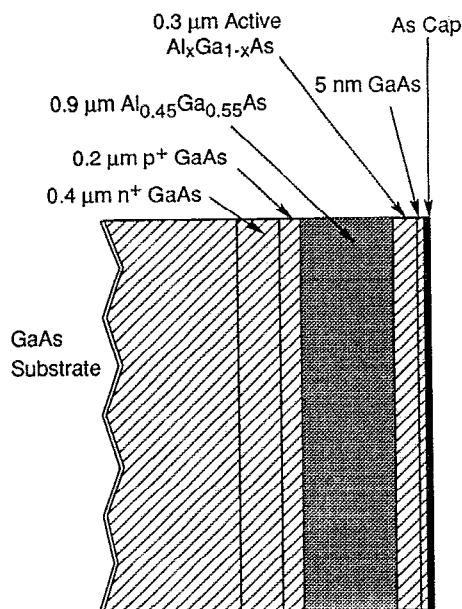
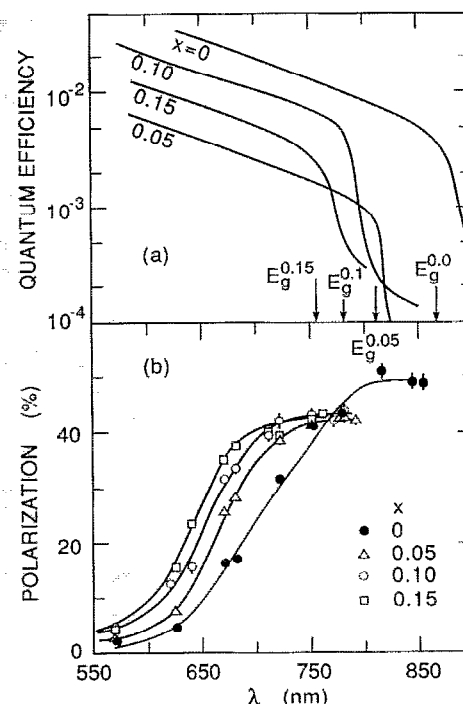FIG. 1. Schematic diagram of the sample structure.

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.

II. EXPERIMENT

For the present experiment, thin $Al_xGa_{1-x}As$ 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 5×10^{18} 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-μm-thick n-type GaAs (Si doped to 5×10^{17} cm^{-3}) followed by a 0.2-μm-thick p-type GaAs (Be doped to 5×10^{17} cm^{-3}). Then, a 0.9-μm-thick layer of p-type $Al_{0.45}Ga_{0.55}As$ (Be doped to 5×10^{18} cm^{-3}) was grown, followed by the active layer of p-type $Al_xGa_{1-x}As$ (Be doped to 5×10^{18} cm^{-3}). The $Al_{0.45}Ga_{0.55}As$ intermediate layer serves as a potential barrier to isolate the active $Al_xGa_{1-x}As$ 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 μm. A thin GaAs layer was grown on top of the active $Al_xGa_{1-x}As$ layer to prevent oxidation of aluminum in the active layer.[11] The thickness of the cap GaAs layer was 5 nm for the $x=0.05$ and $x=0.10$ samples, and 10 nm for the $x=0.15$ sample. After the MBE growth, the sample was cooled to below room temperature in about 3 h and was then exposed to an arsenic beam for 10 min 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 Cu$K\alpha$ 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 h) 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.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the measured photoelectric quantum efficiencies (Q.E.) as a function of the photon wavelength for the three $Al_xGa_{1-x}As$ samples and the 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 toward shorter wavelength with increasing aluminum concentration in accord with the increase in band-gap energy.

Figure 2(b) shows the electron polarization as a function of excitation photon wavelength measured within 5 h 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 toward 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 Ciccacci *et al.* for AlGaAs (Ref. 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) Since the effectiveness of the cap GaAs layer against oxidation of the $Al_xGa_{1-x}As$ was uncertain, the $x=0.05$ and 0.10 samples were grown with a 5-nm-thick cap layer, while for the $x=0.15$ sample the thickness was increased to 10 nm. No difference in the maximum polarization was observed, as shown in Fig. 2(b).

(2) For the 10-nm cap layer of an additional $x=0.10$ sample, the first 5 nm (nearest the active layer) was graded from $x=0.10$ to $x=0.0$. This procedure was used to remove any possible band discontinuities in the conduction bands of the active $Al_xGa_{1-x}As$ and the cap GaAs layers. Such a band discontinuity might be responsible for electron scatterings and consequent spin depolarization. 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. Figure 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 $Al_xGa_{1-x}As$, a superlattice structure of $(GaAs)_7$-$(AlAs)_1$ with an effective aluminum fraction $x=0.125$ was grown using phase-locked epitaxy.[17] This
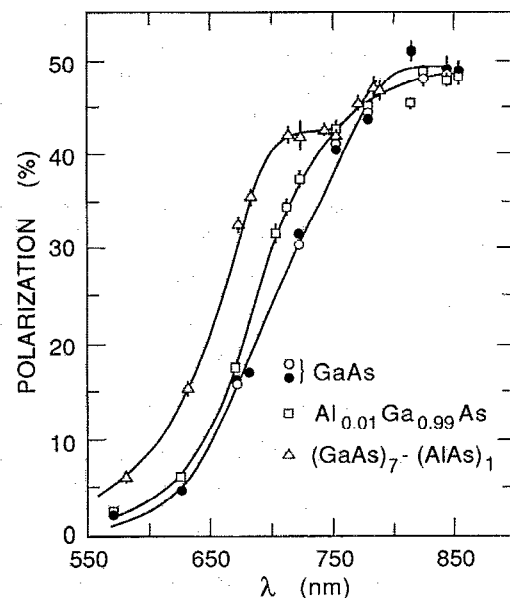

FIG. 3. Electron-spin polarization as a function of excitation photon wavelength for some of the additional samples grown to investigate possible depolarization effects of AlGaAs: the two GaAs samples (solid and open circles), the $x=0.01$ AlGaAs sample (square), and the $(GaAs)_7$-$(AlAs)_1$ superlattice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

material is expected to have a band-gap energy close to 1.61 eV, the value expected for an alloy $Al_{0.125}Ga_{0.875}As$. However, due to the superlattice structure, the actual band-gap energy may be slightly larger than this value, and an energy-band splitting is expected between heavy- and light-hole bands. 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. From these studies, it was concluded that the spin depolarization effect seen in the $Al_xGa_{1-x}As$ samples with nominal $x=0.05$, 0.10, and 0.15 values was associated with the aluminum in the samples.

IV. 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 toward 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.

[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. B **44**, 259 (1981).

[3] T. Maruyama, R. Prepost, E. L. Garwin, C. K. Sinclair, B. Dunham, and S. Kalem, Appl. Phys. Lett. **55**, 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. B **46**, 4261 (1992); T. Nakanishi, H. Aoyagi, H. Horinaka, Y. Kamiya, T. Kato, S. Nakamura, T. Saka, and M. Tsubata, Phys. Lett. A **158**, 345 (1991); H. Aoyagi, H. Horinaka, Y. Kamiya, T. Kato, T. Kosugoh, S. Nakamura, T. Nakanishi, S. Okumi, T. Saka, M. Tawada, and T. Tsubata, *ibid.* **167**, 415 (1992).

[6] T. Omori, Y. Kurihara, T. Nakanishi, H. Aoyagi, T. Baba, T. Furuya, K. Itoga, M. Mizuta, S. Nakamura, Y. Takeuchi, M. Tsubata, and M. Yoshioka, Phys. Rev. Lett. **67**, 3294 (1991); Y. Kurihara, T. Omori, T. Nakanishi, H. Aoyagi, T. Baba, K. Itoga, M. Mizuta, S. Nakamura, Y. Takeuchi, M. Tsubata, and M. Yoshioka, Nucl. Instrum. Methods A **313**, 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, 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 h.

[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**, 4395 (1982); J. Kirschner, H. P. Oepen, and H. Ibach, Appl. Phys. A **30**, 177 (1983); F. Ciccacci, H.-J. Drouhin, C. Hermann, R. Houdre, and G. Lampel, Appl. Phys. Lett. **54**, 632 (1989), W. Hartmann *et al.,* Nucl. Instrum. Methods A **286**, 1 (1990).

[11] F. Ciccacci, H.-J. Drouhin, C. Hermann, R. Houdre, and G. Lampel, Appl. Phys. Lett. **54**, 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**, 1922 (1985).

[13] T. F. Kuech, D. J. Wolford, R. Potemski, J. A. Bradley, K. H. Kelleher, D. Yan, J. P. Farrell, P. M. S. Lesser, and F. H. Pollak, 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] All measurements were made within 5 h of a cathode activation so that the polarization measurements would not have to be corrected for the slow increase of the polarization with time. The increase in polarization with time is generally understood to be due to a rising vacuum level.

[16] F. Ciccacci, S. F. Alvarado, and S. Valeri, J. Appl. Phys. **53**, 4395 (1982).

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