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Observation of Electron Polarization above 80 % in Photoemission from Strained III-V Compounds*

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ABSTRACT

Spin-polarized electron photoemission has been investigated for strained III-V compounds; 1) strained $\mathrm{In_xGa_{1-x}As}$ epitaxially grown on a GaAs substrate, and 2) strained GaAs grown on a $\mathrm{GaAs_{1-x}P_x}$ buffer layer. The lattice mismatched heterostructure results in a highly strained epitaxial layer, and electron spin polarization as high as 90% has been observed.

Polarized electron sources have wide applications in many branches of physics.[1] The use of polarized electron sources with linear electron accelerators is a mature field generally requiring high intensity sources. For example, the SLAC Stanford Linear Collider requires peak currents of about 16A in a 2.5 nsec pulse at 120 Hz. These requirements can be met using photoemission from Negative-Electron-Affinity (NEA) GaAs, and this is the technique adopted for linear electron accelerators. The symmetry of GaAs is such that the maximum polarization is limited to 50% due to the valence band degeneracy of the heavy- and light-hole bands at the Γ point. Much effort has been devoted to achieving higher polarization. The basic approaches involve removing the degeneracy of the valence bands and selectively exciting a single transition for the GaAs type materials or using crystals such as the ternary chalcopyrites which already have the appropriate band structure.[2]

This paper reports significant enhancement of electron polarization above 50 % from NEA photocathodes. The samples for this experiment were 1) a heterostructure of InGaAs epitaxially grown on a GaAs substrate,[3] and 2) a heterostructure of GaAs epitaxially grown on a GaAsP buffer layer. Under these conditions, the epitaxial layer is expected to be highly strained by the lattice mismatch. Strain induces a valence band splitting which permits optical excitation of a single band transition, thus leading potentially to 100% polarization of the photoemitted electrons.

The theory relating strain to band structure has been discussed extensively in the literature.[4] The band structure of the strained layer is altered such that the heavy-hole and light-hole valance bands are no longer degenerate in energy at the Γ point, and the energy splitting is then proportional to the strain. A suitably thin epitaxial layer grown on a lattice mismatched substrate incorporates a biaxial compressive strain in the plane of the interface and a tensile strain along the growth direction. The strain dependent energy levels of the heavy-hole (HH) and light-hole (LH) bands relative to the conduction band are given by:[5]

$$E^{C,HH} = E_0 + \delta E_H - \delta E_S,$$

$$E^{C,LH} = E_0 + \delta E_H + \delta E_S - (\delta E_S)^2/2\Delta_0 + \cdots$$

where E_0 is the direct band gap of fully relaxed InGaAs or GaAs and Δ_0 is the spin orbit splitting. The quantities δE_H and δE_S represent the hydrostatic shift of the center of gravity of the $P_{3/2}$ multiplet and the linear splitting of the $P_{3/2}$ multiplet respectively, and are given in terms of the biaxial strain ϵ parallel to the interface by:

$$\delta E_H = 2a[(C_{11} - C_{12})/C_{11}]\epsilon$$

$$\delta E_S = b[(C_{11} + 2C_{12})/C_{11}]\epsilon$$

where the parameters a and b are the interband hydrostatic pressure and uniaxial deformation potentials, respectively, and the C_{ij} are the elastic-stiffness constants appropriate to the compounds. Since the biaxial strain ϵ is compressive for the present structures, the effect of strain is to increase the band gap energy and to remove the degeneracy of the heavy-hole and light-hole levels such that $E^{C,HH} < E^{C,LH}$.

The InGaAs samples were grown at the Electronics Research Laboratory of the University of California at Berkeley. The samples grown were a thin strained

InGaAs epilayer (thin sample) and a thick relaxed InGaAs layer (thick sample). The substrate material used was (100) *n*-type GaAs (Si doped to 5×10^{18}cm^{-3}). Since heavy *p*-type doping is necessary to achieve a NEA surface, GaAs buffer layers were grown at 600°C to change the carrier type: a 0.6 μm thick *n*-type GaAs (Si doped to 6×10^{18}cm^{-3}) followed by a 0.2 μm thick *p*-type GaAs (Be doped to 6×10^{18}cm^{-3}). The substrate temperature was then reduced to 550°C for the growth of the InGaAs layer. The thin sample had a 0.1 μm thick *p*-type $\mathrm{In_xGa_{1-x}As}$ layer (Be doped to 2×10^{18}cm^{-3} for the first 600 Å and to 4×10^{18}cm^{-3} for the final 400 Å), and the thick sample a 1.14 μm thick *p*-type $\mathrm{In_xGa_{1-x}As}$ layer (Be doped to 2×10^{18}cm^{-3} for the first 11000 Å and to 4×10^{18}cm^{-3} for the final 400 Å). The indium concentration was nominally x=0.13, and the agreement between the indium concentration of the two samples was estimated to be δx= ± 0.01. After the MBE growth, the sample was cooled to room temperature and was exposed to an $\mathrm{As_4}$ beam for about 10 minutes to deposit a 200-500 Å arsenic protection layer. This protection layer was later removed during heat-treatment prior to the first cathode activation.

The strained GaAs sample was grown by the Spire Corporation[6] using Metal-Organic-Chemical-Vapor-Deposition (MOCVD). A 0.25 μm thick *p*-type GaAs buffer layer was grown on a (100) *p*-type GaAs substrate oriented two degrees towards (110) direction. In order to produce a strain relieved $\mathrm{GaAs_{1-x}P_x}$ (x=0.28) layer on GaAs, a 2.5 μm-thick $\mathrm{GaAs_{1-x}P_x}$ layer was grown with an increasing phosphorous fraction from 0 to x to accommodate the lattice mismatch, followed by an additional 2.5 μm-thick $\mathrm{GaAs_{1-x}P_x}$ layer with a fixed phosphorous fraction (x=0.28). The lattice mismatched GaAs epitaxial surface layer was then grown on this buffer. The epitaxial surface layers were *p*-type doped with zinc to a value of 4-6$\times 10^{18}$cm^{-3}. In order to preserve an atomically clean surface the sample was anodized to form an oxide layer of about 100 Å on the GaAs surface.[7] The oxide layer was later removed in ammonium hydroxide.

The electron spin-polarization was measured by Mott scattering at 65 keV in a system described elsewhere.[8] Prior to installation in the system, the sample was degreased sequentially in boiling solutions of trichloroethylene, acetone, and methanol. After the sample installation the gun was baked at 220°C for about 80 hours and at 150°C for 24 hours to achieve the necessary ultrahigh vacuum. During the bake, the sample was maintained at about 270°C by a resistive heater at the back of the cathode support structure. The final pressure during the subsequent polarization measurements was less than 10^{-10} Torr. The cathode was activated to obtain a NEA surface using cesium and nitrogen-trifluoride. Prior to activation, the cathodes were heat-treated for 2 hours at 450°C. This relatively low temperature was used to protect the strained layer structure. For bulk GaAs, temperatures in the range of 600-650°C are normally used.

Fig. 1(a) and (b) show the measured electron spin polarization as a function of excitation photon energy for the 0.1 μm-thick InGaAs sample and the 1.14 μm-thick InGaAs sample, respectively. The experimental uncertainty shown in the figure includes the statistical error only. In the energy region greater than 1.41 eV, the observed electron polarization is consistent with the previous measurements on thin-GaAs samples.[9] Although electrons produced in the InGaAs layer can also contribute in this region with a lower polarization, their contribution to the net spin polarization is negligible because of the much larger photoemission from the

GaAs layer. However, in the energy region between 1.34 and 1.40 eV where the photoemission from GaAs is diminished, the spin polarization is lower due to lower spin polarization in photoemission from the InGaAs layer. In the energy region smaller than 1.34 eV, the spin polarizations of the two samples show a significant difference. The polarization of the 0.10μm-thickness sample is observed to increase sharply at about 1.34 eV reaching 71% at about 1.26 eV. The sharp enhancement at about 1.34 eV corresponds to the expected gap energy between the light-hole band and the conduction band for an indium concentration between 0.121 and 0.133, values consistent with the uncertainty in the indium concentration and the thin sample X-ray analysis. The corresponding energy range is indicated by the shaded region in Fig. 1(a). The sample still has significant photoemission and high polarization at 1.25 eV which is beyond the expected heavy-hole to conduction band energy difference of 1.30 eV. This can be explained by a partial strain relaxation in the epilayer causing the heavy- and light-hole bands to converge towards the relaxed InGaAs valence band located at 1.25 eV. The partial strain relaxation may also explain why the maximum polarization did not reach 100%. On the other hand, the polarization of the 1.14 μm-thick sample remains at 40% and does not show any enhancement. The observed 40% polarization is consistent with the values measured for other bulk III-V compounds.

Fig. 2 shows the measured spin polarization (data points) and cathode quantum efficiency (solid curve) at room temperature as a function of excitation photon energy for the strained GaAs sample. The band gap energy of GaAsP and the calculated heavy-hole band gap energy expected for this sample are shown by the arrows in the figure. In the energy region greater than about 1.7 eV, both GaAsP and GaAs layers contribute to the photoemission, resulting in an increase of the quantum efficiency and a small decrease in the polarization. In the energy region smaller than 1.7 eV, the photoemission from GaAsP diminishes sharply as the excitation photon energy decreases, and the major contribution to the photoemission can come only from the GaAs layer. The polarization is observed to increase sharply at about 1.54 eV reaching 90% at about 1.46 eV. The sharp polarization enhancement at 1.54 and the maximum polarization at 1.47 eV correspond to the expected gap energies $E^{C,LH}$ and $E^{C,HH}$, respectively. A similar polarization enhancement was also observed by Nakanishi *et al.* in photoemission from epitaxial GaAs grown on a thick GaAsP buffer layer.[10] The photocurrent lifetime was measured for this sample at a wavelength of 825 nm yielding an effective lifetime of 168 hours.

In conclusion, the spin polarization has been measured for photoemitted electrons from strained and un-strained InGaAs layers, and a strained GaAs. Polarization in excess of 70% was observed for the 0.1μm-thick strained InGaAs sample. Polarization for the 1.14μm-thick un-strained sample was 40% and consistent with the values of bulk III-V compounds. Polarization as high as 90% was observed for strained GaAs grown epitaxially on a thick GaAsP buffer layer. The observed polarization enhancement of the strained samples is due to the strain-induced energy level splitting of the valence band.

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FIGURE CAPTIONS

Fig. 1 Electron spin-polarization as a function of excitation photon energy for the 0.1 μm-thick InGaAs sample (a) and for the 1.14 μm-thick InGaAs sample (b). The shaded region in Fig. 1a shows the expected light hole to conduction band energy difference compatible with the indium concentration uncertainty and the thin sample X-ray analysis.

Fig. 2 Electron spin-polarization as a function of excitation photon energy (data points), and cathode quantum efficiency as a function of excitation photon energy (solid curve) for strained GaAs sample. The band gap energies of GaAsP (dashed arrow) and the calculated heavy-hole band gap energy (solid arrow) are indicated in the figure.

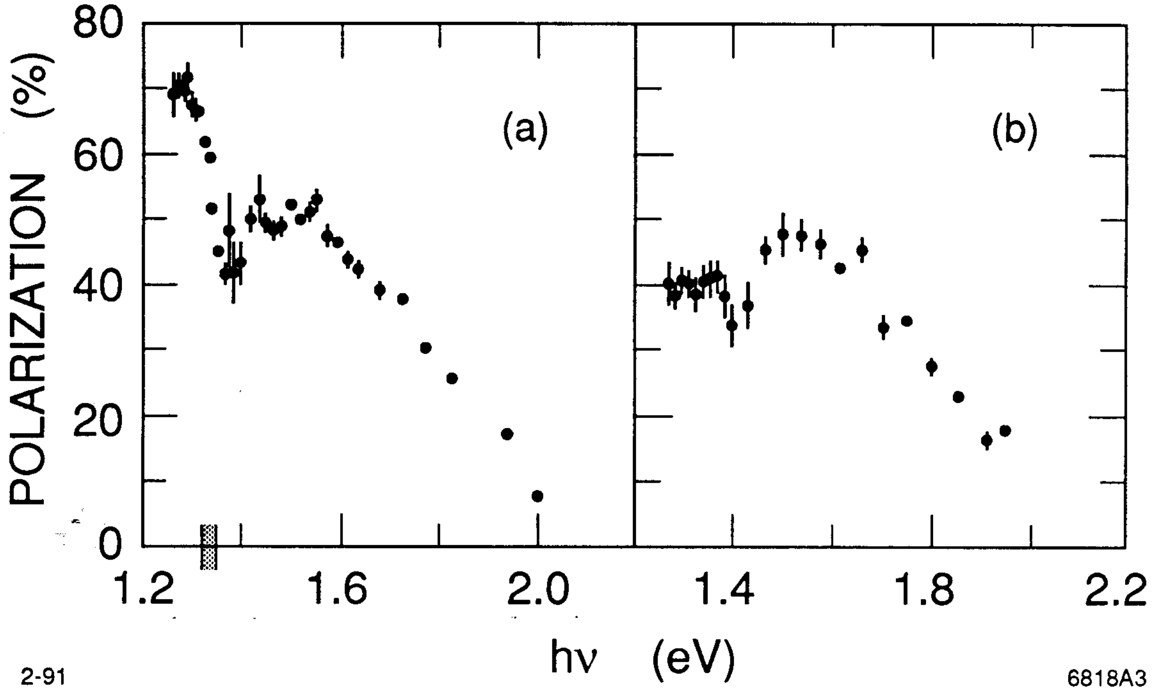

Fig. 1

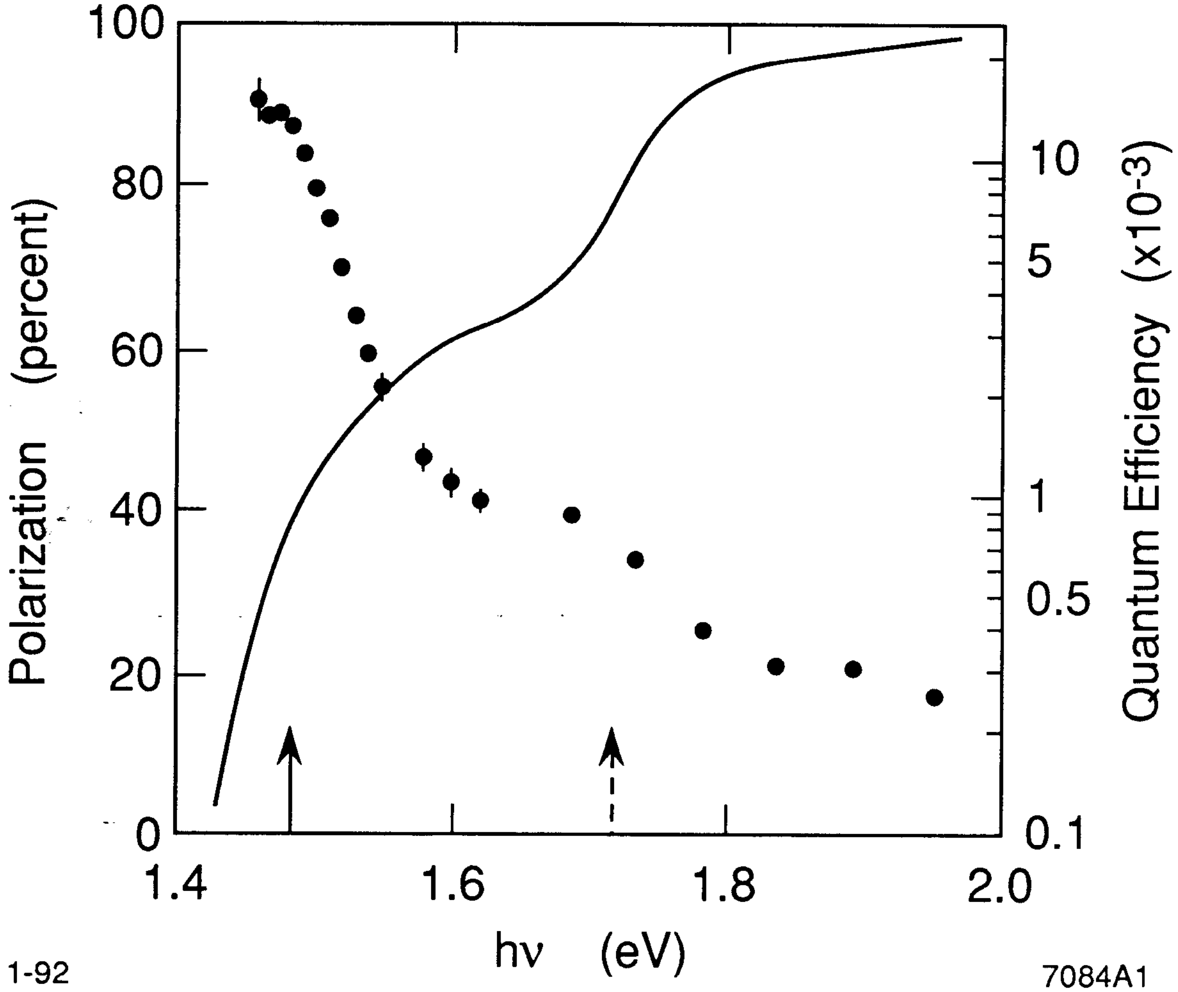
100
80
60
40
20
0
Polarization (percent)
10
5
1
0.5
0.1
Quantum Efficiency (x10-3)
1.4
1.6
1.8
2.0
hν (eV)
1-92
7084A1

Fig. 2