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HIGH POLARIZATION PHOTOCATHODE R&D AT SLAC*

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ABSTRACT

This paper describes recent progress on the development of high polarization photocathodes for polarized electron sources. A strained InGaAs cathode has achieved a maximum electron-spin polarization of 71% and has demonstrated the strain enhancement of polarization for the first time. Strained GaAs cathodes have yielded polarizations as high as 90% with much higher quantum efficiency.

1. Introduction

Polarized electron sources based on negative-electron-affinity GaAs were pioneered at SLAC.[1] The original PEGGY II source produced 2×10^{11} e- per bunch at 120 Hz with an average spin polarization of 37%. The maximum polarization of this type of source was limited to 50% due to the valence-band degeneracy of the heavy-hole and light-hole bands of GaAs. Much effort has been devoted to achieving higher polarization by primarily focusing on the following three types of photocathodes: 1) ternary chalcopyrites which naturally have the appropriate band structure, 2) GaAs-AlGaAs superlattices and 3) strained materials. These materials do not have a valence band degeneracy and selective excitation of a single transition is possible. Earlier efforts at SLAC were devoted to studies of the first two types of photocathodes.[2]

When a thin layer of a crystal A is grown on a different crystal B with a slightly <u>smaller</u> lattice constant, crystal A may grow pseudomorphically, introducing a biaxial compressive strain in the plane of the interface. The strain alters the band structure of crystal A such that the strain dependent energy difference of the heavy-hole and light-hole bands relative to the conduction band is given by

$$E_0^{CHH} = E_0 + \delta E_H - \delta E_S$$
$$E_0^{CLH} = E_0 + \delta E_H - \delta E_S - (\delta E_S)^2/2\Delta_0$$

where E_0 is the direct band gap of fully relaxed crystal A and D_0 is the spin orbit splitting. The quantities dE_H and dE_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 e parallel to the interface by

$$\delta E_H = 2a\,[(C_{11}-C_{12})/C_{11}]\,e \quad \text{and}$$
$$\delta E_S = b\,[(C_{11}+2C_{12})/C_{11}]\,e$$

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. Since the biaxial strain e is compressive, the effect of the strain is to increase the band gap energy and remove the degeneracy of the heavy-hole and light-hole levels such that the heavy-hole band moves up in energy and the light-hole band moves down relative to the unstrained case. This energy splitting makes it possible to preferentially excite the heavy-hole band by tuning the excitation photon energy. An electron spin polarization of higher than 50% is then in principle possible for photoexcited electrons: the heavy-hole band to conduction band transition would result in 100% electron spin polarization. On the other hand, if an epitaxial layer were grown on a crystal with a <u>larger</u> lattice constant, a tensile strain would develop in the plane of the interface lifting the light-hole band higher in energy than the heavy-hole band. Selective excitation of the light hole band results in a polarization of -100% opposite in sign from the 50% polarization obtained when the heavy-hole and light-hole bands are degenerate.

When a lattice-mismatched layer is grown on a substrate, the misfit between the layers is accomodated by the elastic strain in the epitaxial layer. However, as the epitaxial layer exceeds a critical thickness, misfit dislocations are generated which begin to relieve the strain. Although the idea of using the strained photocathodes for increasing polarization has been known since the late 1970s, it was generally considered impractical for the polarized electron source application because the critical thickness is typically 100Å.[3] However, recent experimental studies on lattice-mismatched layers have revealed that most of the lattice strain is preserved to thicknesses much beyond the critical thickness and significant strain relief can be observed only above a second critical thickness of about 1000Å.[4]

2. Strained InGaAs grown on GaAs[5]

The electron spin polarization was measured for two samples with a InGaAs layer epitaxially grown on a GaAs substrate with InGaAs thicknesses of 0.1 µm and 1.14 µm. The thin sample is expected to be highly strained, while the thick sample is relaxed. Figures 1(a) and (b) show the measured electron spin polarization as a function of excitation photon wavelength for the 0.1 µm thick and the 1.14 µm thick samples, respectively. In the wavelength region longer than 880 nm, the

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Presented at the 10th International Symposium on High Energy Spin Physics, Nagoya, Japan, November 9-14, 1992 photoemission *from* GaAs diminishes sharply since the excitation photon energy is smaller than the GaAs band gap, and the major contribution to the photoemission can come only *from* the InGaAs layer The spin polarizations of the two samples show a significant difference The polarization of the 0.10 μm-thick sample is observed to increase sharply at about 925 nm reaching 71% at about 980 nm The sharp enhancement at about 925 nm corresponds to the expected gap energy between the light-hole band and the conduction band for the sample On the other hand the polarization of the 1.14 μm-thick sample remains at 40% and does not show any enhancement

3. Strained GaAs grown on InGaAs

It is well known that the electron-spin polarization increases when the photoemission quantum efficiency decreases In particular polarizations higher than 50% have been observed for positive-electron-affinity surfaces It is important to demonstrate that the polarization enhancement observed for the thin InGaAs sample is indeed due to the crystal strain and not due to a positive-electron-affinity surface As mentioned in the introduction a tensile strain in the plane of the interface should produce a spin polarization opposite to a compressive strain To test this prediction a third sample was grown with a 0.1 μm-thick GaAs layer grown on a thick InGaAs (which is also epitaxially grown on a GaAs substrate)[6] As shown in Fig 1(c) the polarization decreased from +50% changed its sign and reached 66% This behavior is totally consistent with the expectation from the strain induced effect

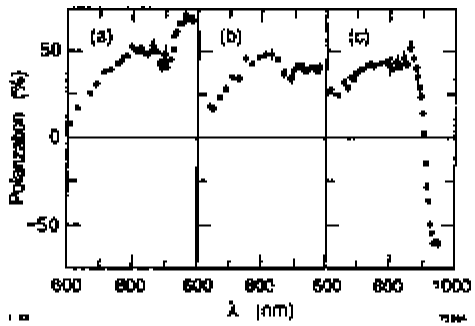

Figure 1 Electron-spin polarization as a function of excitation photon wavelength for a) 0.1 μm InGaAs b) 1.14 μm InGaAs and c) 0.1 μm GaAs

4 Strained GaAs grown on GaAsP[7]

A systematic study of strain effects on electron polarization has been made using samples with GaAs epitaxially grown on a $GaAs_{1-x}P_x$ buffer layer Samples with varying epitaxial layer thickness and varying buffer layer phosphorus concentration were used to cover a range of strains, and the electron spin polarization and quantum efficiency were measured for each sample as a function of excitation photon energy

Table I *summarizes* the parameters for the *five samples* studied the phosphorus fraction (x) the GaAs epitaxial layer thickness the lattice-mismatch, the measured strain as a per cent of full strain and the critical thickness

TABLE I Strained GaAs samples

Sample	1	2	3	4	5
x	0.210	0.243	0.279	0.244	0.238
GaAs thickness (μm)	0.11	0.15	0.11	0.20	0.30
Lattice mismatch (%)	0.76	0.86	1.01	0.88	0.86
Measured strain (%)	76	85	87	81	61
Critical thickness (Å)	133	110	92	110	113

Figure 2 shows the measured electron spin polarization as a function of excitation photon wavelength for all the samples The polarization of samples 1, 2 and 3 shows a systematic shift of the location of the polarization enhancement toward shorter wavelength as the phosphorus fraction is increased This shift is consistent with the expected change in the energy gap E_0^{CLH} due to increased strain The maximum polarization at the photon energy corresponding to the gap energy E_0^{CHH} increases from 82% to 90% as the phosphorus fraction is increased most likely due to a more selective excitation of the heavy-hole band, since the heavy-hole light-hole splitting increases from 50meV to 67meV for these samples

Although the buffer layers for samples 4 and 5 have the same phosphorus fraction as sample 2 the polarization of these samples shows a systematically different behavior The polarization enhancement shifts toward longer wavelength as the GaAs thickness is increased from 0.15 μm (sample 2) to 0.20 μm (sample 4) and to 0.30 μm (sample 5) For sample 5 photoemission is observed beyond the expected band gap energy E_0^{CHH} This is a strong indication that the lattice is partially relaxed and that the heavy and light-hole band energies are merging towards the values expected for relaxed GaAs However even though there is considerable relaxation of the strain the maximum polarization of both samples reaches more than 80% Since the epitaxial layer of sample 5 is about 30 times thicker than the equilibrium critical thickness this high polarization demonstrates a significant persistence of lattice strain

Figure 3 shows the measured quantum efficiency as a function of excitation photon wavelength for all the samples As expected, the quantum efficiency increases with increasing GaAs epitaxial layer thickness However the gain in quantum efficiency in the high polarization region is offset by a commensurate decrease in polarization due to the increased relaxation of the sample strain For the present samples, the highest quantum efficiency that corresponds to at least 80% polarization is 0 13%, measured for sample 4

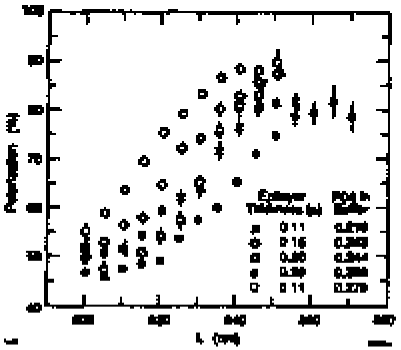

Figure 2 Electron-spin polarization as a function of wavelength for the strained GaAs samples

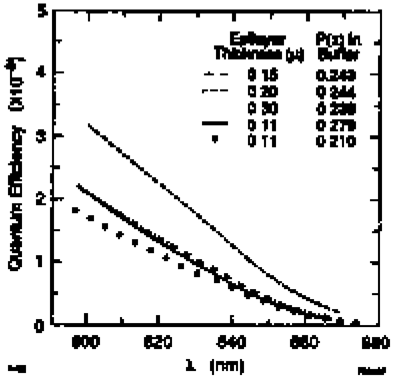

Figure 3 Quantum efficiency as a function of wavelength

5. *Conclusions*

The effect of strain on electron-spin polarization has been systematically studied with InGaAs and GaAs photocathodes Polarization in excess of 70% was observed for the 0 1 mm-thick strained InGaAs establishing the first observation of strain enhancement of electron-spin polarization for photoemitted electrons Polarization as high as 90% was observed for strained GaAs and the highest quantum efficiency corresponding to at least 80% polarization was 0 13%

6. *References*

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