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Two Novel Approaches for Electron Beam Polarization from Unstrained GaAs

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Two novel approaches to producing highly-polarized electron beams from unstrained GaAs were tested using a micro-Mott polarimeter. Based on a suggestion by Nakanishi [1]], two-photon photoemission with 1560 nm light was used with photocathodes of varying thickness: 625μm, 0.32μm, and 0.18μm. For each of these photocathodes, the degree of spin polarization of the photoemitted beam was less than 50%. Polarization via two-photon absorption was highest from the thinnest photocathode sample and close to that obtained from one-photon absorption (using 778 nm light), with values 40.3±1.0% and 42.6±1.0%, respectively. The second attempt to produce highly-polarized electrons used one-photon emission with 778 nm light in Laguerre-Gaussian modes with different amounts of orbital angular momentum. The degree of electron spin polarization was consistent with zero, with an upper limit of ~3% for light with up to ±5ħ of orbital angular momentum. In contrast, the degree of spin polarization was 32.3±1.4% using circularly-polarized laser light at the same wavelength, which is typical for thick, unstrained GaAs photocathodes.

[1] T. Matsuyama *et al.* in *Proceedings of the 4th Pacific Rim Conf. on Lasers and Electro-Optics* 164-5 (2001)

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1. Introduction

Polarized electron sources are important parts of particle accelerators like the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab, where polarized electrons probe nuclear structure, dynamics of strong interactions, electro-weak nuclear physics including parity-violation, and physics beyond the Standard Model [2]. The first GaAs-based polarized electron source used at an accelerator [3] provided beam polarization ~35%, with polarization limited to less than 50% due to the degeneracy in the $^2P_{3/2}$ energy level of unstrained bulk GaAs [4],[5]. Significantly higher beam polarization was obtained in the 1990s by introducing an axial strain within the GaAs crystal structure, eliminating this degeneracy [6-8]. By using strained-superlattice GaAs/GaAsP structure, today's beam polarization routinely exceeds 80% [9][10]. In addition to having significantly lower quantum efficiency (QE), these high polarization strained-GaAs photocathodes are expensive and delicate compared to unstrained bulk GaAs [8].

This paper presents the results of two methods, both of which modified the source GaAs illumination, designed to improve the polarization of photoelectrons produced from unstrained bulk GaAs. Both experiments measured photoelectron polarization using a compact retarding-field micro-Mott polarimeter [11]. The first method used circularly polarized light of wavelength 1560 nm, which is half of the band-gap, to create photoemission from two-photon absorption [12]. The second technique attempted to couple spin from light with orbital angular momentum into the electrons in the GaAs photocathode [13].

2. Electron Polarization from Two-Photon Photoemission

2.1 Introduction

Matsuyama et al. proposed using two-photon absorption as a mechanism to obtain high polarization from unstrained GaAs [1]. They reasoned that quantum mechanical selection rules associated with the simultaneous absorption of two photons of circularly-polarized light at half the band-gap energy would provide a means to populate the conduction band with electrons of just one spin state yielding, in principle, completely polarized electrons in the conduction band immediately following excitation (Figure 1). Subsequently, Matsuyama et al. [14] performed an experiment that relied on electron-hole photoluminescence measurements (but not photoemission) with electron-hole recombination fluorescence polarization measured to be 58%. This value was used to infer an electron polarization of 95% at the time of excitation to the conduction band.

In contrast with Ref. [14], Bhat et al. [15] provided a more detailed analysis of two-photon absorption in semiconductors, and predicted that polarization via two-photon absorption in GaAs should be less than 50%. Photoluminescence experiments using differential transmission pump/probe techniques indicated a nascent polarization equal to 48%, in support of their predictions [15][16].

Because of these differing sets of predictions and experiments, our experiment was designed to evaluate two-photon emission as relevant to providing a polarized electron source. Presented is a direct measurement of electron beam polarization from two-photon excitation of GaAs, of three different sample thicknesses. For each sample, the degree of spin polarization of the photoemitted beam was less than 50%, contradicting both the prediction and photoluminescence measurements of Matsuyama et al. [1][14]. Polarization via two-photon absorption was highest from the thin photocathode samples (~40%) and was comparable to that obtained via one-photon 778 nm absorption (~ 43%).

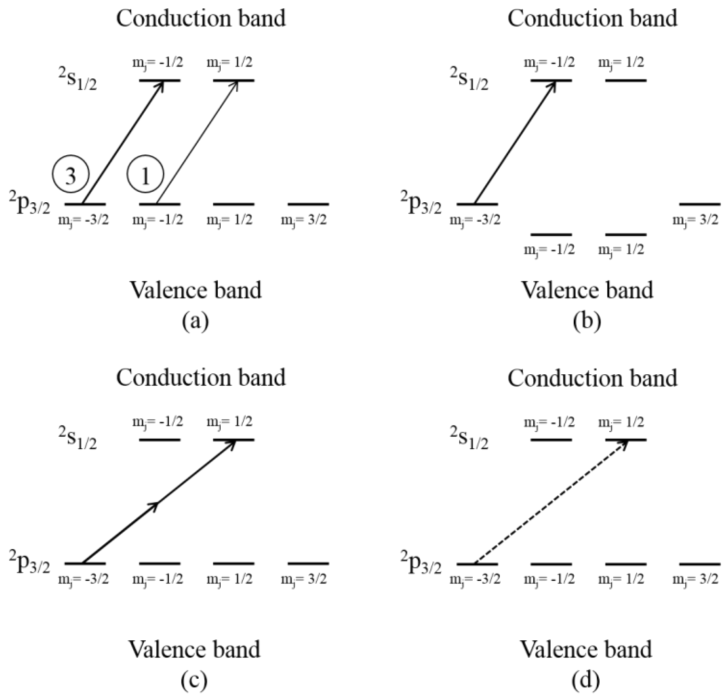

Figure 1: Various means to populate the conduction band of GaAs with circularly-polarized light: a) one-photon excitation of unstrained GaAs, b) one-photon excitation of strained GaAs, c) two-photon excitation of unstrained GaAs with photons having energy equal to half that of the band-gap as predicted in Ref [1], and d) excitation of unstrained GaAs using one-photon of OAM light with m=2. The circled values in (a) indicate relative transition probabilities for unstrained GaAs.

2.2 Experimental setup

The apparatus consisted of a low-voltage polarized electron source chamber for installing and activating photocathodes, a beam transport section, and a micro-Mott retarding-field polarimeter, as seen in (Figure 2). Three different wafers of unstrained GaAs were used as photocathode material. One sample, known as the “thick” sample (625 μm), was unstrained bulk GaAs, and the “thin” samples (0.18 and 0.32 μm) were grown on thick GaAs substrates, with an intervening barrier layer of p-$Al_{0.3}Ga_{0.7}As$ that was ~0.9 μm thick. The barrier layer ensured that only electrons produced in the thin GaAs layer could reach the photocathode surface. For all GaAs samples, the photocathode was biased at -268V using batteries and the emitted electron beam was delivered to the micro-Mott polarimeter using a 90° electrostatic deflector [17] and electrostatic steering lenses [18].

For photoemission from one-photon absorption, the light source was a simple 778 nm low-power diode laser operating either in DC or RF pulsed-mode at repetition rates from 250 to 1000 MHz. For two-photon absorption, light at half the band-gap energy is needed. The 1560 nm source was a gain-switched fiber-coupled diode “seed” laser and fiber-amplifier that produced up to 5 W average power at repetition rates from 250 to 2000 MHz, with optical pulse widths of ~ 40 to 60 ps, depending on the rate [19]. By using short-pulse light, high peak power was obtained to enhance the two-photon absorption process, which normally results in a very low quantum efficiency. With a maximum laser peak intensity of ~$2x10^5$ W/cm^2, two-photon emission had a maximum QE of ~$1x10^{-7}$%, as compared to ~1.5 % measured in the one-photon process. The entire apparatus, including optics used, is described more thoroughly in other publications [11][12].

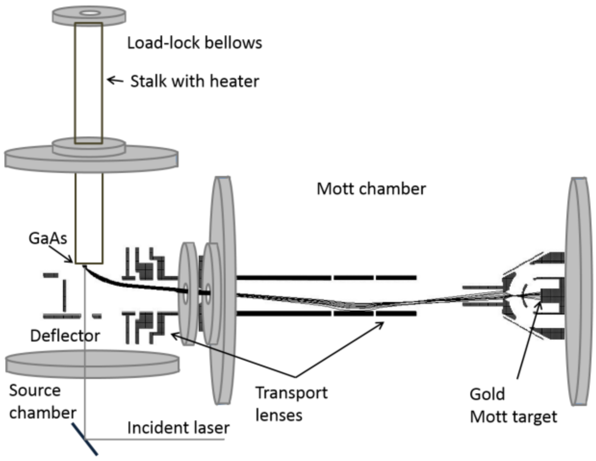

Figure 2: Schematic of the experimental apparatus, with source chamber, transport, and Mott chamber sections. The black lines directed through the lenses represent electron trajectories simulated by SIMION.

2.3 Results and Discussion

The polarization asymmetry of the electron beams generated with one- and two-photon excitation was measured using the micro-Mott polarimeter, in the manner described in [11] using a gold target biased at 20 kV and with a maximum electron energy loss in the target $\Delta E=0$. For the thick GaAs sample, using light at 778 nm, which corresponds to one-photon absorption, repeated measurements gave a polarization of 33.4±0.8 %, typical of bulk GaAs. At 1560 nm, corresponding to two-photon photoemission, the measured polarization was 16.8±0.4 %, which was significantly lower than any prediction.

One reason for the lower-than-expected value of polarization associated with two-photon emission, as seen in the thick GaAs sample, is that 1560 nm light has a much longer absorption depth in GaAs than does 778 nm light. This longer depth leads to more depolarization of the excited electrons. Not clear from the bulk sample measurements was if the lower-than-expected two-photon polarization was due either to these long electron diffusion paths to the cathode surface or to an unexpectedly low value of initial two-photon polarization, in contradiction to ref. [15]. The photoelectron polarization was thus measured using samples with thicknesses significantly less than the expected electron spin-depolarization length [20]. The thin GaAs samples, with active thickness of 0.18 μm or 0.32 μm, were analyzed, and for the thinnest GaAs sample, the polarizations of both one- and two-photon absorption were only slightly different, ~ 43% vs. 40%, respectively, as seen in Table 1.

Table 1. Photoemitted electron polarization taken for one- and two-photon absorption for three different samples of GaAs.

	Photoelectron Polarization %	
Active Thickness	One-photon (778 nm)	Two-photon (1560 nm)
0.18 μm	42.6±1.0	40.3±1.0
0.32 μm	44.0±1.1	36.0±0.9
Bulk Material	33.4±0.8	16.8±0.4

While theoretically one-photon absorption should give 50% polarization, there are many effects which reduce the polarization, even with thin active layers, and the measured ~43% polarization at 778 nm is typical of thin unstrained GaAs [21]. The convergence of the two-photon polarization to that of the one-photon polarization with decreasing sample thickness indicates an initial two-photon polarization close to 50%, as proposed by Bhat et. al [15]. As such, two-photon absorption appears to be incapable of producing an electron beam with polarization greater than 50%.

3. Electron Polarization from Photoemission using Light with Orbital Angular Momentum

3.1 Introduction

Light beams with azimuthal phase dependence – often referred to as “twisted light” or ”vortex light” —can carry orbital angular momentum (OAM) about their axis of propagation. Light with OAM is different from conventional circularly-polarized light that possesses only one unit (±ħ) of spin angular momentum (SAM) per photon in that it can possess arbitrarily large values of OAM, ±*m*ħ, where *m* is a positive integer [22].

As detailed above, GaAs has long been used to generate spin-polarized electron beams via photoemission using light with SAM [23]. We explored the idea of creating spin-polarized electron beams by imparting angular momentum to electrons in the conduction band of bulk GaAs using light with OAM. Such an idea is appealing; given the large amount of OAM that vortex beams can carry, one might expect that at least part of it could be transferred through spin-orbit coupling to the photoelectrons emitted from the surface. As explained in ref [13], there is a lack of calculations in the literature relating to this possible coupling, and as such, we designed our experiment designed to test for this possible spin-orbit coupling. Polarization measurements were consistent with zero, suggesting that light with OAM does not couple effectively to the internal motion of electrons in a semiconductor, at least when the focused transverse laser spot size is ~200 μm or larger.

3.2 Experimental setup

In this experiment, the main apparatus was similar to that used for two-photon photoemission, as described above (Figure 2), with only a difference in the choice of light source. For this experiment, two linearly-polarized 780 nm laser beams of comparable intensity were directed at diffraction gratings with screw dislocations, which produced two linearly-polarized laser beams with Laguerre–Gaussian (LG) transverse spatial modes, corresponding to light with OAM [22][23][26]. The amount of the OAM was determined by the choice of grating, and the two beams had opposite senses of rotation. The light was then directed to the GaAs photocathode, where they had transverse laser spot sizes of at least 200 μm, and produced electron beams that were delivered to the micro-Mott polarimeter [11]. A more complete description of this apparatus, including further detail on the production of OAM light, can be found in ref. [13].

3.3 Results and Discussion

The functionality of the apparatus, and in particular the retarding-field micro-Mott polarimeter biased at +20 kV, was verified using circularly-polarized laser light, and was found to be 32±0.87(pol)±0.48%(sys), wherein “pol” and “sys” refer to “polarization” (i.e., the uncertainty resulting solely from the Mott measurement) and “systematic” error respectively.

Four different diffraction gratings were used to create light with ±1, ±2, ±3 or ±5 units of OAM. Repeated polarization measurements, shown in Figure 3, indicate that the polarization for all topological charges is less than ~3% and is consistent with zero. The error bars reflect an absolute uncertainty of ±0.05% in the polarization measurements as well as an absolute systematic uncertainty of ±1.77% (added linearly). Due to the method used to calculate polarization from the measured Mott asymmetry [13], the latter systematic uncertainty is completely dominated by effects associated with changes in the spatial profile of the OAM light on the photocathode as the sign of the topological charge is flipped. These spatial profile changes slightly alter the efficiency to detect the Mott scattered electrons, which causes systematic uncertainty, and this effect becomes more pronounced with bigger beam sizes, associated with higher values of *m*. Taking this systematic effect into account, we find that for light with OAM, electron polarization, P_e = 0.73±0.04(pol)±1.77(sys)%; 0.71±0.06(pol)±1.77(sys)%; 0.30±0.06(pol)±1.77(sys)%; 0.16±0.06(pol)±1.77(sys)% for m = 1, 2, 3, and 5 respectively, with all results consistent with zero, as seen in Figure 3.

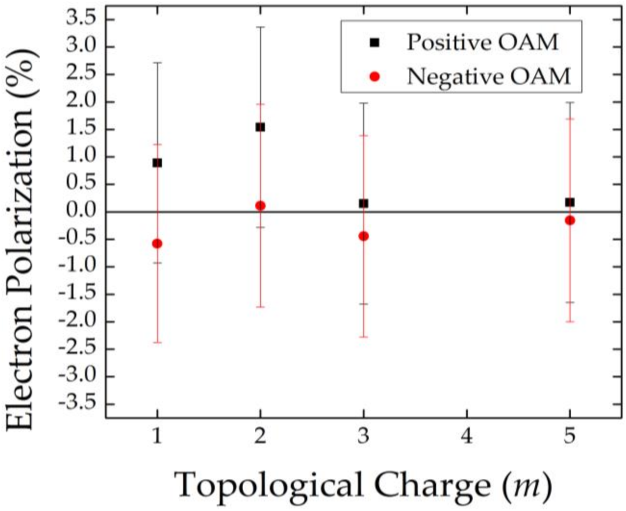

Figure 3: Electron polarization measurements for beams with various amounts of OAM. Error bars are discussed in the text.

4. Summary of Both Techniques

Two different novel techniques were used to generate electron beams from unstrained GaAs. For the first, two-photon photoemission using 1560 nm light produced electron beams from varying thicknesses of unstrained GaAs photocathodes: 625 μm, 0.32 μm and 0.18 μm. Polarization via two-photon absorption from the thickest sample was approximately half that obtained via one photon absorption, and had the same sign. For the thinner samples, polarizations via two and one-photon absorption were comparable, ~ 40% to 43%, respectively, with the degree of spin polarization of the photoemitted beam always less than 50%. These results indicate that the two-photon transition depicted in Figure 1c does not occur with significant probability, which is a result that when coupled with the low QE of two-photon emission precludes the use of this technique in creating polarized electron beams.

The second technique tested the spin-orbit coupling of light with OAM with electrons in GaAs. For all values of OAM used, the polarization results were consistent with zero, and these null polarization results, as well as the lack of obvious dependence of photocathode QE on *m* value, imply at most a relatively weak coupling between the OAM of the incident laser beam and the valance-band electrons of the GaAs bulk. A definitive statement about such coupling strengths will obviously require more precise experiments. Further experiments investigating spin-polarized photoemission using OAM light from GaAs would consist principally of improvements to the optical system described, reducing spatial variations or creating smaller beam sizes.

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