



## REPORT ON POLARIZED ELECTRON SOURCE AND ELECTRON POLARIMETRY WORKSHOP

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### INTRODUCTION

A two day workshop on polarized electron sources and electron polarimetry was held during the week before the 1988 Spin Physics Symposium. A report on the only previous such meeting, held at SLAC in 1983, has been published in the proceedings of the 1984 Spin Physics Conference held in Marseille.<sup>1</sup> The current workshop drew an attendance of 40 people from 23 institutions; 13 in the US, and 10 from Japan, western Europe, and the USSR. This factor of two increase in both the number of attendees and the number of institutions represented, compared to the 1983 meeting, is partially a result of the growing community of polarized electron experimenters, and partially a result of holding the workshop in conjunction with the Spin Physics Symposium.

As has been noted before, unlike the situation with either polarized hadron beams or polarized targets, polarized electrons see their greatest application in fields outside high energy and nuclear physics. Thus, for example, substantially over half of the technical content of both workshops has come from people working in other areas of physics. Currently, the largest application of polarized electron sources and low energy electron polarimetry is in the field of surface physics.

Although presently nearly all major linear or recirculating electron accelerators include polarized electron capabilities in their experimental program planning, and many very difficult experiments using polarized electrons are being planned, there is relatively little effort being devoted to polarized electron source development. Very tight budgets, and the fact that polarized source development involves experimental techniques unfamiliar to most high energy and nuclear physicists both seem partially responsible. Given the impact that polarized source improvements could have on the quality of the physics results, and on the accelerator operational costs to obtain these results, the current modest level of source development work is puzzling.

It seems quite clear that the polarized source improvements most important for application in high energy and nuclear physics are unlikely to come from other areas of physics. Most polarized source users are quite satisfied with the modest polarization of the GaAs source, as their measurements involve sizeable

asymmetries. Sources with operational lifetimes of tens of hours, and current capabilities of a few microamperes, are quite adequate for applications in surface physics, condensed matter physics, and atomic physics, where the cross sections are enormous by our standards, and the experiments delightfully short. Experimentalists in these areas are far more likely to turn their attention to their physics interests, rather than to seek the relatively small gains which polarized source improvements would bring to their experiments.

In our field, we seek polarized sources offering the highest possible polarization, a high degree of freedom from systematic effects on polarization reversal, and the capability of delivering very high peak and/or average currents for periods of time matched to our experiments, i.e. many hundreds of hours. Though polarized sources with these characteristics would certainly be widely employed if they were available, the demand for them is relatively weak outside of high energy and nuclear physics. If such sources are ever to be developed, high energy and nuclear physics will have to provide the support for that development.

There has been a considerable convergence in the fields of polarized electron sources and low energy electron polarimetry since the 1983 workshop. At that workshop, we considered the prospects for polarized electron production based upon a number of phenomena involving optical or magnetic polarization of electrons in both free atoms and bulk matter. Today, with a single exception, all of the operating polarized sources are of the GaAs type. That single exception, a source based upon the chemi-ionization of optically pumped helium metastables, is well matched to many of the beam requirements anticipated at the growing number of CW or near CW electron accelerators.

Similarly, in 1983 we looked at a variety of ways to measure electron polarization at relatively low energies. Today, the old standard, Mott scattering, remains the dominant method for such measurements. This technique has been developed to the point where ultra-high vacuum compatible Mott polarimeters, of major dimension 8 cm, are commercially available.<sup>2</sup> Several methods for doing absolute electron polarization measurements are under active development. Currently, absolute measurements with a precision better than 1% are being made, and in the near term, precisions of a few per mil are anticipated. Ultimately, it may be possible to measure electron polarization with a precision of one per mil. This leads to the prospect that one might do high precision measurements of the Sherman function, under well defined conditions of inelasticity and geometry, and thus dramatically reduce the uncertainties associated with Mott scattering measurements made at laboratories everywhere.

As noted earlier, many of the workshop participants were from fields outside high energy and nuclear physics. Most of these participants were unwilling to prepare written reports of their presentations for publication in the conference proceedings. In some cases, our speakers presented the work of several groups, or even several laboratories. As much of this work is unpublished elsewhere and

was not formally submitted to this conference, I have referenced the speaker and his institution where appropriate. Readers requiring further information should contact these speakers directly. In some cases I may be able to provide greater detail as well.

### THE GaAs SOURCE

Though the GaAs polarized source has been described in many places we will, for the sake of completeness, briefly discuss its major features here.<sup>3</sup> There are two basic aspects to this source: (1) illumination of the semiconductor with circularly polarized light of an appropriate wavelength to produce polarized electrons in the conduction band of the material; and (2) treatment of the semiconductor surface by monolayer coverages of alkali metals and oxidants to lower the work function to the point where these polarized electrons may be emitted.

To see how the conduction band polarization arises, we first note the band structure of GaAs in the vicinity of the minimum direct bandgap, shown in an  $E(k)$  versus  $k$  plot in Figure 1. Near this bandgap minimum, the electron states are well characterized by the single electron quantum numbers indicated. It is easy to understand, using only the relevant Clebsch-Gordan coefficients, that transitions between the  $p_{3/2}$  valence band and the  $s_{1/2}$  conduction band caused by 100% circularly polarized photons produce -50% electron polarization in the conduction band. As one moves to photon energies larger than the minimum bandgap energy, the electron states are less well characterized by single particle quantum numbers, and the polarization produced decreases slowly. Ultimately, as one reaches photon energies sufficient to cause transitions from the spin-orbit split off  $p_{1/2}$  valence band, the conduction band polarization drops to zero. These various transitions are illustrated in Figure 1.

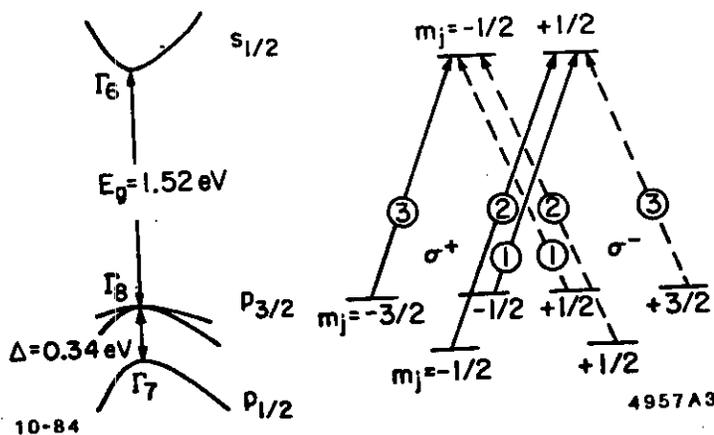


Figure 1:  
The band structure of GaAs near the bandgap minimum is shown on the left. On the right, the relative transition rates between the valence and conduction bands for right (left) circularly polarized photons are shown on the solid (dashed) lines. For photon energies between  $E_g$  and  $E_g + \Delta$ , only transitions from the  $p_{3/2}$  valence band are possible.

Electrons excited to the conduction band by optical illumination are bound in the material by some 4 eV, and thus cannot be emitted. The addition of monolayer coverages of an alkali like cesium, and an oxidant like fluorine or oxygen, to the surface of a p-type semiconductor of adequate bandgap, creates a surface dipole moment such that the vacuum energy level outside the semiconductor lies below the energy minimum of the conduction band in the bulk material. This condition, known as negative electron affinity (NEA), is quite easily established on clean surfaces of p-type GaAs. A quantum efficiency of 1% at the operating wavelength of a GaAs source translates to 6.5 mA of beam current per watt of light. As quantum efficiencies of several percent are readily obtained, this source is able to deliver very substantial currents using very modest optical sources.

In practice, the GaAs source does not deliver the theoretically possible beam polarization. Polarizations ranging between 25% and 45% have been reported for various GaAs sources. The distribution of these reported polarization values has been characterized as "bimodal", with one group of values clustered around 28%, and another around 40%. The reasons for this are not well understood, nor, in fact, are the details of all the possible spin relaxation processes in diffusion through, and emission from, the bulk semiconductor. To this one must add the fact that all the reported polarization values were measured in various "one of a kind" experimental setups, none of which is absolutely calibrated. It seems difficult to ascribe the considerable spread in these polarization values to different experimental techniques and/or experimenters, leaving one with the feeling that as yet unidentified factors are involved.

The optical absorption becomes small as the photon energy approaches the bandgap energy, i.e. for those photons giving the highest polarization. Thus, the most highly polarized electrons are produced throughout a relatively deep region in the bulk semiconductor, and must diffuse from these depths to the surface before they can be emitted. It is reasonable to assume that the greater the depth from which they must diffuse, the more likely they are to be depolarized. One might then expect to achieve the highest possible polarization by artificially limiting this diffusion by the use of a suitably thin sample of material. As the appropriate thickness is less than a micron, it is necessary to produce the thin sample on a substrate which will not contribute to the electron yield. In addition, as a chemical cleaning which removes many microns of material is normally employed on bulk samples as part of the process of preparing a sufficiently clean surface for photocathode fabrication, a different means has to be found to assure a clean surface.

A single such thin sample was prepared some years ago at KFA Jülich, which gave a measured polarization of 49%, nearly the theoretical maximum.<sup>4</sup> Given that the Jülich result was reported for only a single sample, and that polarizations measured in different laboratories and from different samples have shown

considerable variability, a group from Illinois, Wisconsin, CEBAF, and SLAC has prepared and measured samples of four different thicknesses, both to reproduce the Jülich result, and to determine the optimum thickness for polarized source applications.<sup>5</sup> The samples were prepared by molecular beam epitaxy at the University of Illinois. A layer of GaAlAs with a bandgap significantly larger than that of GaAs was first grown on a thick (635 micron) GaAs substrate. The thin GaAs layer was grown on the GaAlAs barrier layer, and was capped with a few hundred Angstrom layer of antimony. The GaAlAs layer prevents electrons produced in the bulk substrate from diffusing to the surface, and produces no electrons itself because of its larger bandgap. The antimony serves to protect the GaAs surface from contamination, and is easily removed by heating once the sample is safely installed in the ultra-high vacuum of the electron gun.

The results from measurements of polarization versus wavelength for four different thickness samples are given in Figure 2. The 49% polarization observed from the thinnest sample agrees very well with the earlier Jülich result. The anticipated thickness dependence is clearly seen. These results indicate that any thickness less than about 0.4 micron will give the maximum polarization, and that a thickness of 0.9 microns is basically indistinguishable from bulk GaAs. This is an important result, for it shows that one can closely approach the theoretical maximum polarization from a GaAs source by the use of a suitable sample. Many custom epitaxial growth firms and university laboratories are well equipped to grow appropriate samples.

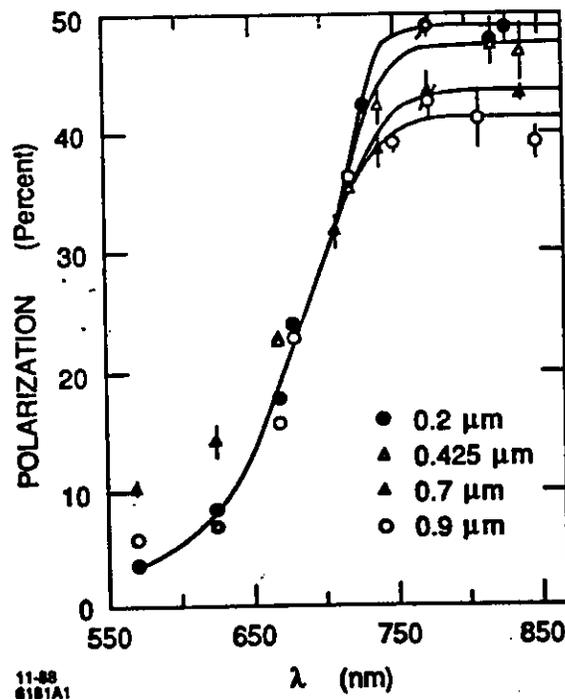


Figure 2: Polarization versus wavelength from four different thickness GaAs layers.

Photoemission cathodes are normally prepared on clean p-type semiconductor surfaces, such as GaAs, by exposure to monolayer quantities of cesium and oxygen. It was reported at the 1983 workshop that the use of cesium and fluorine (the latter obtained by the use of  $\text{NF}_3$  rather than elemental fluorine) gave consistently better quantum efficiencies and improved resistance to degradation by residual gas poisoning, compared to the use of oxygen. This work has continued, and GaAs photoemission cathodes with measured  $1/e$  lifetimes of  $10^4$  hours in actively pumped ultra-high vacuum systems have been prepared at SLAC.<sup>6</sup> Perhaps more importantly, it has also been demonstrated that these photocathodes can deliver many hundreds of coulombs of beam without excessive degradation. The important feature in the total charge delivery experiments was to assure that the emitted electron beam could not produce desorbed gases which could reach the photocathode and poison it. These results indicate that it is possible to construct GaAs polarized sources which are robust enough to last, both time-wise and total charge-wise, for a complete high energy physics experiment, without requiring photocathode re-activation.

A group at Mainz has completed a very thorough and interesting study of the formation of NEA surfaces on both GaAs and the wider bandgap GaAsP.<sup>7</sup> They measured the change in the work function, the quantum yield, and the emitted electron polarization as a function of alkali metal coverage using all the alkali elements, and in some cases oxygen or fluorine as well. They found that the addition of fluorine to a cesiated GaAs surface changed the work function only slightly, but dramatically increased the quantum yield. This indicates that it is the character of the surface barrier which changes with fluorine exposure, and may give some clues as to why the use of fluorine gives better results than the use of oxygen in making NEA photocathodes on GaAs.

### SEMICONDUCTOR PHOTOCATHODES FOR HIGHER POLARIZATION

The results currently obtained with GaAs indicate that the polarization of the basic source can be brought very close to its theoretical limit, and that with appropriate care, long operating life and large total charge delivery are practical. To improve the polarization beyond this point, it is necessary to somehow remove the degeneracy at the top of the valence band. Several ways have been proposed to accomplish this. They include the application of a uniaxial stress perpendicular to the emitting surface, the growth of multi-layer semiconductor heterostructures which create a uniaxial modulation of the bandgap energy in the dimension perpendicular to the surface, and the use of materials in which the offending degeneracy is naturally absent. Efforts, to date unsuccessful, are being made in each of these areas.

In evaluating candidate semiconductors for more highly polarized sources, one often chooses to measure the polarization of the recombination light emitted

after optical pumping, rather than going through the complete process of producing a photoemission cathode on the sample and measuring the polarization of the emitted electrons. The idea here is that the matrix element for the recombination of a conduction band electron with a valence band hole is directly related to the matrix element for exciting a valence band electron to the conduction band. Thus, a measurement of the polarization of the recombination light samples the polarization of the conduction band electrons. The polarization of electrons actually emitted from a photocathode will, of course, always be higher than the value inferred from the recombination light polarization, as the emitted electrons no longer have the possibility of depolarizing while waiting to recombine. Recombination light polarization measurements are not simple exercises, although they may be easier than learning how to make photoemission cathodes on arbitrary samples of new materials and doing a complete electron polarization measurement. In general, neither path is particularly easy.

One way to produce uniaxial stress in a sample is to grow it by some epitaxial method on a substrate of different lattice constant. In accommodating to this lattice mismatch, the grown layer is strained. The thickness of this strained layer can be increased to the point at which the stored elastic energy is sufficient to generate crystal damage, such as dislocations and microcracks. The strains which can be produced in a suitably thin layer are enormous compared to those which can be generated by the application of external force to the sample. Large strains are called for, since the typical band splitting is on the order of a few meV per kbar of internal stress, and splittings of many tens of meV are required for useful polarization improvements.

A group at Osaka Prefecture University is investigating strain effects in InGaAsP/InP layers grown on InP substrates.<sup>8</sup> They have observed an improvement in the luminescence polarization which they attribute to the internal strain, but have not yet measured the emitted electron polarization. There are other pairs of materials which may form good strained layers for polarized source applications. GaAs grown on silicon, for example, has a 4% lattice mismatch, and the advantages that we already know how to prepare a photocathode on GaAs, and that substrate electrons are unlikely to be a problem from silicon. This particular strained layer system is currently receiving a great deal of material science effort, due to promising electronic applications. While the strained layer method may improve the polarization, it remains to be demonstrated that a strained layer system will tolerate without degradation the various steps involved in repeated cathode activations. Hopefully answers to some of these questions will be available before too much longer.

One can produce semiconductor structures with a uniaxial variation in the bandgap energy, with or without any particularly dramatic strain effects, by growing a succession of alternating layers of two materials with different bandgaps. GaAs-AlGaAs multilayer structures are the most common example,

as the two materials have very similar lattice constants and are relatively easy to grow. Some samples of these multilayers have been demonstrated, by photoluminescence measurements, to produce highly polarized conduction band electrons.<sup>9</sup> In the samples studied to date, a significant fraction of the bandgap discontinuity lies in the conduction band. The highly polarized conduction band electrons are in fact bound in the conduction band wells. To extract these electrons, it is necessary to transport them perpendicular to the bandgap discontinuities, which is problematic. The electrons need to be trapped in the wells to be highly polarized, but need to be transported through the barriers to be emitted.

Two attempts have been made to extract highly polarized electrons from photocathodes fabricated on such samples. One, done at KFA Jülich, apparently failed to obtain a photoemission threshold low enough to have seen a polarization improvement had it existed.<sup>10</sup> The second result, from SLAC, saw an enhancement in both the polarization and the quantum yield at the correct wavelength for excitation of highly polarized electrons to the conduction band.<sup>11</sup> However, the effect was quite small, and corresponded to adding a small component of highly polarized electrons to a "background" of normally polarized electrons from GaAs. The SLAC researchers concluded that the difficulty in producing a higher polarization came from the problem of transporting the conduction band electrons through the large number of barriers in the thick semiconductor heterostructure.

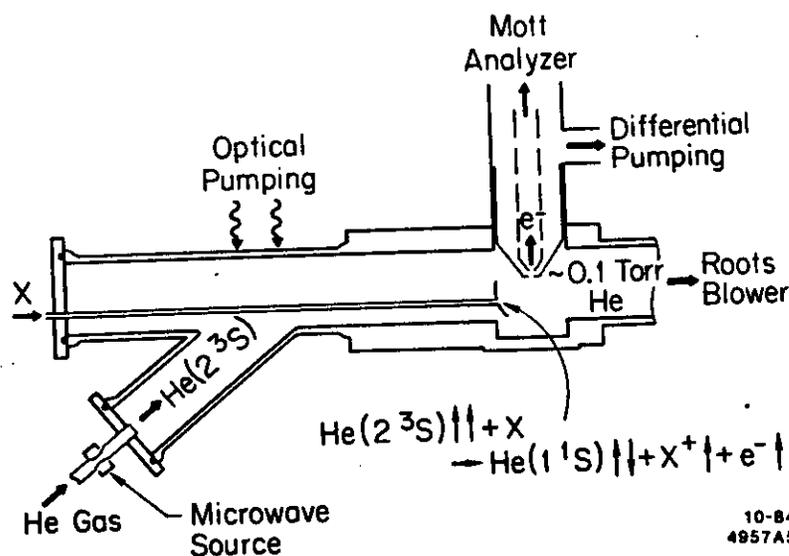
Most recently, a group at Ecole Polytechnique has studied the problem of producing high electron polarization from multilayer semiconductor samples.<sup>12</sup> They have concluded that the experimental results to date are not decisive, and that there is no reason why the method should not work. They have experimentally demonstrated electron emission through a small number of conduction band barriers, and thus conclude that a suitable multilayer structure should give a high emitted electron polarization. An appropriate structure should have shown a high luminescence polarization, have a very thin GaAs cap layer (ca. 100 Angstroms), and be very carefully doped to avoid Fermi level difficulties. Unfortunately, it may be some time before such a carefully engineered and well characterized sample is available.

A final approach to high polarization from semiconductor photoemitters is to seek a material which naturally lacks the valence band degeneracy. One promising class of such materials is the so-called II-IV-V<sub>2</sub> chalcopyrites. These semiconductors are ternary analogues of the III-V compounds (such as GaAs and InP), and all have the valence band degeneracy removed by virtue of having two cations, rather than one. In addition, almost all II-IV-V<sub>2</sub> chalcopyrites have a significant tetragonal distortion, which also removes the degeneracy. The valence band degeneracy in these materials is typically split on the order of 100 meV. Another such family of materials is the I-III-VI<sub>2</sub> chalcopyrites, the ternary analogues of the II-VI semiconductors. Both the II-VI semiconductors and their

candidate. Unfortunately, this compound is relatively difficult to grow. It grows peritectically from the melt, making bulk growth methods difficult. Epitaxial samples have been prepared by MOCVD, but only very thin layers have been produced so far. Recently, sizeable samples of  $\text{CdSiAs}_2$  have been produced by chemical vapor transport at Konstanz.<sup>16</sup> At the workshop, it was reported that both  $\text{CdSiAs}_2$  and  $\text{CdGeP}_2$  are being grown by the Bridgeman method at Tohoku. These samples are currently being evaluated by the photoluminescence method.<sup>8</sup> Finally, the Osaka Prefecture University group is evaluating the I-III-VI<sub>2</sub> compound  $\text{AgGaSe}_2$ , also by photoluminescence.<sup>8</sup> It is gratifying to see the increased effort being devoted to various chalcopyrite compounds, but many difficulties remain to be resolved before these materials will be employed in polarized electron sources.

### THE HELIUM CHEMI-IONIZATION SOURCE

In the helium chemi-ionization polarized electron source, a stream of metastable  $2^3\text{S}$  and  $2^1\text{S}$  helium atoms is produced in a microwave discharge source. Optically pumping the  $2^3\text{S}$  to  $2^3\text{P}$  transition with 100% circularly polarized light of adequate intensity produces  $2^3\text{S}$  metastables with an electronic polarization closely approaching 100%. The  $2^1\text{S}$  metastables are not polarized by this optical pumping. Following the optical pumping, the metastables are chemi-ionized by interaction with a gas such as  $\text{CO}_2$ . Since the chemi-ionization process leaves the electron spin untouched, the  $2^3\text{S}$  states produce highly polarized electrons, and the  $2^1\text{S}$  states unpolarized electrons. This source is shown schematically in Figure 3.<sup>17</sup> In the example shown in Figure 3, the electrons are extracted with a transverse polarization.



**Figure 3:** The helium chemi-ionization polarized electron source.

function, and attempts to account for inelasticity by doing a target thickness extrapolation. It has been pointed out that even the mathematical form of the target thickness extrapolation is unknown, and as a consequence, there is an absolute uncertainty on the order of 5% associated with Mott measurements.<sup>20</sup>

One way to avoid the problems of the target thickness extrapolation is to build a Mott polarimeter in which the inelasticity accepted by the detectors can be limited. By making measurements with an exceptionally small inelasticity, followed by measurements with the same apparatus and target foil but with much greater inelasticity, it is possible to calibrate the large inelasticity case against the near-zero inelasticity case, and thus obtain the benefits of the very much higher counting rate available with larger inelasticity. The development of Mott polarimeters which permit the inelasticity to be controlled has been pursued extensively by the Rice University group, and has resulted in the perfection of an impressively compact Mott polarimeter, of major dimension about 8 cm., which is being marketed commercially.<sup>21,2</sup> Similarly compact diffuse scattering polarimeters have been developed at the NBS.<sup>22</sup>

The NBS group has been working for some time to improve the figure of merit for low energy electron polarimeters, primarily for applications in surface analysis. They reported that the use of thorium as a Mott scatterer, as opposed to the far more conventional gold, led to an improvement of 30% in the effective Sherman function. This improvement, coupled with the greater scattered intensity from the higher Z thorium, leads to an overall improvement in polarimeter figure of merit of better than 1.7. Of course, thorium is a chemically far more active material than gold, so it remains to be seen if it will provide Sherman functions stable with time.<sup>23</sup>

Several groups are now pursuing the goal of high accuracy absolute electron polarimetry. The experimental approaches include Mott double scattering, mirror plane scattering from single crystal platinum, measurement of the circular polarization of helium radiation following excitation by polarized electrons, and preparation of an electron beam of known polarization from chemi-ionization of helium metastables. A very impressive program at Münster is working on the first three methods simultaneously. They have already measured the absolute value of a Sherman function to better than 1% by observing the circular polarization of helium radiation.<sup>24</sup> Hopster reported absolute measurements of the Sherman function by comparing the Mott scattering of a polarized beam (from a GaAs source) to the Mott scattering of the same beam reflected from a mirror plane in a platinum single crystal.<sup>25</sup> His results quoted 1/2% precision, and could be obtained in one hour of running time! The Rice University group plans to prepare a low intensity beam of known polarization from a beam of helium metastables. The helium metastable polarization will be measured in a Stern-Gerlach apparatus, and by using argon as the chemi-ionization gas, the electron spin and the metastable spin must be the same.<sup>26</sup> Finally, Gay at

I-III-VI<sub>2</sub> chalcopyrite analogues are less well studied than the corresponding III-V and II-IV-V<sub>2</sub> compounds, and the fabrication of NEA photocathodes is standard practice only on some III-V semiconductors.

One difficulty which arises with the ternary chalcopyrite compounds is the so-called pseudo-direct bandgap. All of these semiconductors have direct bandgaps in the sense that the conduction band minimum lies directly above the valence band maximum in k-space. Though unstated earlier, a direct bandgap is required for generating highly polarized conduction band electrons, since photon induced transitions have  $\Delta k = 0$ . Those II-IV-V<sub>2</sub> chalcopyrites which are analogues of indirect gap III-V compounds, though having a direct gap in the above sense, retain the symmetry of their indirect gap analogue at the conduction band minimum. This situation is called a pseudo-direct gap, and is not uncommon among the II-IV-V<sub>2</sub> compounds. The transition matrix elements at the bandgap minimum of the pseudo-direct compounds have the wrong conduction band symmetry to produce high polarization. In these compounds, one has obtained the desired valence band structure, but has lost the proper conduction band structure! In seeking a candidate chalcopyrite for high electron polarization, one thus needs a compound derived from a direct gap III-V (or II-VI) material, and which also possesses all the other properties necessary for the fabrication of a good photoemission cathode.

There have been very few polarization measurements reported from photocathodes prepared on chalcopyrite samples. ZnSiAs<sub>2</sub> and ZnGeAs<sub>2</sub> were measured at ETH Zurich, using small samples grown by bulk techniques.<sup>13</sup> An epitaxial sample of ZnSiAs<sub>2</sub>, grown by MOCVD, was measured at SLAC.<sup>1</sup> Unfortunately, ZnSiAs<sub>2</sub> has a pseudo-direct bandgap, and showed a polarization comparable to GaAs. Though ZnGeAs<sub>2</sub> has a true direct bandgap, the ETH group was unable to prepare a NEA photocathode on it, presumably because of its small bandgap. Lacking the NEA condition, they were unable to obtain emission from those optical wavelengths expected to produce high polarization.

More recently, excellent quality epitaxial samples of ZnGeAs<sub>2</sub>, grown by MOCVD, have become available.<sup>14</sup> As NEA photocathodes have been prepared on semiconductors with smaller bandgaps than ZnGeAs<sub>2</sub>, it is hoped that the high quality of the MOCVD samples, along with the improved photocathode preparation techniques using fluorine, will permit a NEA condition to be obtained and the potentially high polarization to be demonstrated. By the addition of either phosphorous or silicon to the basic ZnGeAs<sub>2</sub> crystal, an alloy with a larger bandgap can be produced. This alloying should not degrade the emitted electron polarization as long as the bandgap remains direct, much in the way that GaAlAs and GaAs show similar maximum electron polarization as long as the GaAlAs bandgap is direct.<sup>15</sup>

If one sought the ideal chalcopyrite semiconductor for polarized electron applications from the information available, CdSiAs<sub>2</sub> would likely be the prime

The factors which limit the performance of this source are fairly easily identified. Since the  $2^1S$  states do not produce polarized electrons, but are chemi-ionized, their presence in the metastable stream dilutes the polarization. Sufficient laser power to saturate the polarization of the  $2^3S$  metastables is required. This is difficult as the required wavelength,  $1.083\mu$ , is not easily obtained in lasers with adequate power. The intensity is limited by the production and subsequent loss of the  $2^3S$  metastables, and by the efficiency of extracting the electrons after chemi-ionization. Finally, to the extent that electrons produced by other than the chemi-ionization process are present in the final beam, the polarization is further degraded. To date, this source has delivered 80% polarization at  $40nA$ , 70% at  $1\mu A$ , 60% at  $10\mu A$ , and 40% at  $50\mu A$ . It should be noted that this source inherently produces a DC beam. Thus it is relatively well matched to the requirements of CW electron accelerators, but useless for the very high current, short pulse requirements of many low duty cycle accelerators.

There are a growing number of CW electron machines planned or under construction for the study of electromagnetic nuclear physics. In conjunction with these machines, the helium source meets a need which currently cannot be satisfied by the existing GaAs type sources. A group at Rice University, where this source was originally developed, is studying the extent to which the characteristics of this source may be improved or extended, with support from CEBAF and the University of Illinois. It is anticipated that improvements to the laser, the metastable source, the overall source geometry, and the extraction efficiency may produce a source delivering about 90% polarization in a  $100\mu A$  CW beam.<sup>18</sup> The University of Illinois is developing bunching schemes which should deliver at least 50% of this CW beam properly bunched for acceleration in CEBAF.<sup>19</sup> If these goals are met, the helium source would likely replace the GaAs source for a very substantial fraction of all applications at CW electron machines.

## ELECTRON POLARIMETRY

Electron polarimetry for beam energies between a few eV and about 150 keV has historically been accomplished by Mott scattering. This energy range includes virtually all of the polarized electron usage outside of high energy and nuclear physics, and is important in these latter fields for the measurement of electron source polarization. In Mott scattering, one observes the left-right asymmetry caused by spin-orbit coupling in scattering a transversely polarized electron from a high Z nucleus. The analyzing power of Mott scattering is known as the Sherman function. While conceptually straightforward, Mott scattering is experimentally challenging. The measured asymmetry is strongly dependent upon both the inelasticity and the scattering geometry, and the Sherman function is known only through very difficult double scattering measurements, or by reliance upon calculations of uncertain precision. Typically, one relies on some mixture of double scattering measurements and calculations for the Sherman

the University of Missouri is constructing apparatus to compare Mott scattering with the circular polarization of helium radiation, a method he originally suggested.<sup>27</sup> There is clearly dramatic progress in the measurement of absolute electron polarization at low energy, and in intercomparing the different methods for such measurements. In the foreseeable future, one may be able to know values for the Sherman function with better than 1% precision. This will be a great advance for all users of polarized electrons.

There is no similarly dramatic move in high energy electron polarimetry. Here, the techniques are either Møller scattering from the polarized electrons in a magnetized foil, or Compton backscattering of circularly polarized laser light. The only contribution to the workshop on high energy polarimetry came from Mainz, where they have constructed a Møller polarimeter able to measure both the longitudinal and transverse polarization of a high energy beam. The analyzing power for the transverse components is quite small; about 10% of that for the longitudinal component. The longitudinal analyzing power is small itself, with a typical value of about 5%. The Mainz group presented results showing that they were able to measure transverse components of electron spin with about 10% precision.<sup>28</sup>

The Mainz group also showed a very simple polarimeter designed to operate continuously in an electron beam headed for the beam dump. A target is used to produce circularly polarized bremsstrahlung from the longitudinally polarized electron beam. This bremsstrahlung polarization is measured continuously in a simple polarimeter comprised of ionization chambers before and after a block of magnetized iron. Although the analyzing power of this polarimeter is quite small, about  $2 \times 10^{-3}$ , it can be used continuously, and is readily calibrated against the Møller polarimeter. This polarimeter was used to continuously monitor the polarization during the Mainz parity violation experiment.

## SPECIAL TOPICS

Several topics which are important in polarized source technology were briefly discussed. Primary among these were lasers. The semiconductor sources require optical pumping light typically in the near infrared. This is commonly produced by a dye laser tuned to the appropriate wavelength. The acceptable bandwidth for these lasers is quite large. However, the pulse structure of the dye laser must be matched to the accelerator to which the source is attached. This requirement can be troublesome. For the SLC, for example, pulses of nanosecond duration, tens of kW of peak optical power, and 180 Hz repetition rate are necessary. When one adds to these difficult laser specifications the accelerator related demands for pulse-to-pulse stability, temporal stability, and operational lifetime, a highly non-conventional laser is required. Any future linear collider is likely to have far more stringent requirements. The SLAC program to reach the laser requirements for the SLC polarized source was described.<sup>29</sup>

The helium source requires optical pumping to polarize the helium metastables. Since this is a DC source, a CW laser is used. One requires enough narrowband intensity to saturate the helium metastable polarization. Optical power on the order of some tens of mW to perhaps 150 mW appears adequate. The wavelength must be matched to the  $2^3S$  to  $2^3P$  transition, at  $1.083\mu$ . It is currently very difficult to produce adequate optical power at this wavelength. A relatively new solid state laser material, LNA, pumped by a high power argon (or krypton) ion laser is the avenue currently under development at Rice University.<sup>26</sup> An efficient dye for this wavelength range has been reported, but is unavailable either commercially or from its developer. Similarly, a new solid state lasing material, chromium activated forsterite, has been reported to lase at the proper wavelength, but this too is unavailable. These several avenues give some hope that before too long a laser will become available which will help bring the helium source to its full potential.

All electron accelerators involve varying amounts of magnetic beam transport between their injector and the final experiment. Thus the injected polarization is not in general the polarization to reach the experimenter. Furthermore, the magnetic elements to correct the beam polarization at the high energy end of an accelerator would in general be too expensive, take up too much space, generate too much synchrotron radiation, and present difficulties with beam optics. Thus, to deliver the desired polarization to an experiment, it is usually necessary to provide a controllable polarization orientation at the injector. The Mainz group presented a plan for a spin orientation system comprised of a pair of electrostatic deflectors and four double wound solenoids.<sup>28</sup> This scheme possesses good electron-optical properties, and is an attractive alternative to the use of a Wien Filter and solenoid combination.

Finally, two laboratories, Mainz and MIT/Bates, reported that operation of GaAs sources with a continuous optical power density of  $20 \text{ W/cm}^2$  resulted in degradation of the quantum efficiency in the illuminated region. This phenomena is apparently absent with power densities of  $5 \text{ W/cm}^2$ . While the degradation mechanism is not well understood, it represents a practical intensity limit to the GaAs source if it cannot be eliminated. Most current accelerator requirements will not find this limit too restrictive.

## SUMMARY

While there has been real progress since the 1983 workshop, much of this has come from outside of the high energy and nuclear physics laboratories. Low funding, and the small number of people willing or able to devote time to this work are responsible. In the case of semiconductor photocathode sources, progress is strongly hampered by near total absence of sources for the specialized samples required.

Nevertheless, one can now plan with some degree of confidence on long lifetime GaAs sources delivering hundreds of coulombs of 49% polarized electrons.

These developments are a direct result of work in high energy and nuclear labs. The demands for polarized electron beams for the physics programs of the growing number of accelerators for electromagnetic nuclear physics can be expected to spur further developments.

The helium chemi-ionization source is now under very active development. It may very well be improved to the point where it can satisfy virtually all of the requirements for CW or near CW electron accelerators. Even in its present state of development it can satisfy many of the needs for polarized target and large aperture spectrometer experiments.

Electron linear colliders, room temperature linear accelerators, and machines employing pulse stretcher rings require the higher peak currents presently available only from semiconductor photocathode sources. Though there are several promising avenues to pursue, the current efforts are quite modest. There is little demand for improvements to these sources outside our field, and sources of candidate samples are scarce. Any development of these sources will have to be supported with high energy and nuclear physics resources.

Low energy electron polarimetry is in an exciting period of development. The near future offers the prospect of high precision absolute polarization measurements by several methods and from several laboratories. The fact that an electron polarimeter is now commercially available attests to the growth of interest in polarized electron physics in several fields.

Electron polarimetry at high energy is based upon well understood physics, and the measurements are relatively clean. A Møller polarimeter to measure both transverse and longitudinal polarization has been demonstrated. High energy polarimetry still demands developmental work to meet the needs of current experiments, however. Very small beam sizes, unpleasant duty factors, and the requirement for high precision measurements in reasonable time periods all present real challenges to polarimeter designers.

If the vitality apparent in low energy polarimetry shows in the other areas covered by this workshop, the next workshop will be most interesting. It is a great pleasure to organize and attend a workshop with participants from so many fields of physics. Perhaps the broad range of interests of the participants in our small workshop gave it some of the flavor of what physics was like in the "good old days". This man certainly enjoyed it!

## REFERENCES

1. C. K. Sinclair, Jour. de Physique 46, C2-669 (1985).
2. Mott Polarimeters are available from Leisk Engineering Limited, West Sussex, England.
3. D. T. Pierce et al., Rev. Sci. Instrum. 51, 478 (1980).
4. S. F. Alvarado et al., Z. Phys. B44, 259 (1981).

5. T. Maruyama, University of Wisconsin, presentation to this workshop.
6. C. K. Sinclair, in "Advanced Accelerator Concepts", AIP Conference Proceedings No. 156, Amer. Inst. of Physics, New York, 1987, p. 298.
7. W. Gasteyer, Dissertation (1988), Johannes Gutenberg Universität, Mainz. (unpublished)
8. T. Nakanishi, Nagoya University, presentation to this workshop.
9. R. C. Miller et al., in "Proceedings of the 16th International Conference on Semiconductors, Edinburgh, 1978", B. L. H. Wilson, ed. Institute of Physics, London, 1979. p. 1043.
10. S. F. Alvarado et al., Appl. Phys. Lett., 39, 615 (1981).
11. C. K. Sinclair in "High Energy Physics with Polarized Beams and Polarized Targets", C. Joseph and J. Soffer, eds. Birkhauser, Basel, 1981, p. 27.
12. G. Lampel, Ecole Polytechnique, presentation to this workshop.
13. P. Zurcher and F. Meier, J. Appl. Phys. 50, 3687 (1979).
14. G. S. Solomon et al., J. Appl. Phys., to be published.
15. F. Ciccacci et al., J. Appl. Phys. 53, 4395 (1982).
16. M. Kimmel et al., SLAC-PUB 4603, submitted to J. Crystal Growth.
17. L. G. Gray et al., Rev. Sci. Instr. 54, 271 (1983).
18. G. K. Walters, Rice University, contribution to this workshop.
19. L. S. Cardman, University of Illinois, private communication.
20. G. D. Fletcher et al., Phys. Rev. A34, 911 (1986).
21. F. C. Tang et al., Rev. Sci. Instrum. 59, 504 (1988).
22. J. Unguris et al., Rev. Sci. Instrum. 57, 1314 (1986); and Rev. Sci. Instrum., to be published.
23. D. T. Pierce, NIST, presentation to this workshop.
24. J. Goeke et al., Phys. Rev. Lett. 59, 1413 (1987); and G. F. Hanne, Universität Münster, presentation to this workshop.
25. H. Hopster and D. L. Abraham, Rev. Sci. Instrum. 59, 49 (1988).
26. F. B. Dunning, Rice University, contribution to this workshop.
27. T. J. Gay, J. Phys. B16, L553 (1983).
28. E. Reichert, Johannes Gutenberg Universität, contribution to this workshop.
29. F. Perrier, SLAC, contribution to this workshop.