SLAC-PUB-2621
October 1980
(N)

HIGH INTENSITY POLARIZED ELECTRON SOURCES*

Charles K. Sinclair
Stanford Linear Accelerator Center, Stanford, California 94305

ABSTRACT

The status of the polarized electron source development program at SLAC will be reviewed. Emission currents of 60 A, corresponding to a space charge limited current density of 180 A/cm^2, have been obtained from GaAs photocathodes. Electron beam polarization 20% greater than that obtainable from GaAs cathodes has been observed from multilayer GaAs-GaAlAs structures. Work in progress to produce high beam polarization from II-IV-V$_2$ chalcopyrite photocathodes will also be described.

INTRODUCTION

Of all the techniques which have been developed to generate beams of polarized electrons, only photoemission from semiconductor cathodes illuminated by circularly polarized light has proven to deliver beams of both great intensity and excellent control over systematic effects associated with polarization reversal. As such beams are potentially useful as polarized injectors for linear colliders, and for next generation weak-EM interference measurements, we have programs underway at SLAC to develop very high current polarized electron guns, and to increase the beam polarization above that obtainable with gallium arsenide cathodes. This paper is a brief review of what has been accomplished at SLAC with these polarized electron sources, and a progress report on the developmental work we are currently doing.

The first gallium arsenide polarized electron gun for high energy physics use was developed at SLAC to study parity violation in inelastic electron scattering 1. The original design of this source was described in a contribution to the 1976 conference of this series 2. In actual operation, this source delivered beam on a 24 hour per day basis for continuous periods of six weeks, with a long term average beam availability of 93%. Operation was at 120 Hz, rather than the 180 Hz possible, to achieve better pulse to pulse stability. The pulse to pulse instabilities with this source were associated with the laser, rather than being a fundamental limitation. Other laser types have successfully operated with 180 Hz repetition rates and very acceptable pulse to pulse stability.

The long term average polarization was 37%, as opposed to the nominal 43-44% expected from GaAs photocathodes. This was due to a somewhat shorter than optimal operating wavelength for the laser. Again, this is not a fundamental limitation. Following the experimental use of this source, we have operated with a longer wavelength laser, achieving the expected higher polarization.

Operating currents substantially exceeded our anticipations. We regularly observed currents of several hundred mA emitted from the cathodes. We were unable to utilize these high currents in experimental operation as the transport line between the polarized gun and the linac was space charge limited to lower current values, and as the linac itself cannot handle currents much larger than about 80 mA for the full pulse width. We did achieve currents delivered to the experimental target as high as 55 mA.

---

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.
(Invited talk presented at the 1980 International Symposium on High Energy Physics with Polarized Beams and Polarized Target, Lausanne, Switzerland, September 25 - October 1, 1980.)

With the photocathodes operated at room temperature, lifetimes appear to be limited by long term cesium desorption from the cathode surface. Addition of very small amounts of cesium restores room temperature cathodes to their initial quantum efficiencies. We have maintained cathodes for many weeks with only occasional re-cesiation, and have observed cathode 1/e lifetimes of many months at room temperatures.

As the polarization from room temperature GaAs cathodes is typically only about 2/3 of that obtained at liquid nitrogen temperature, we ran our cathodes at LN_2 temperature during the experiment. At this temperature, the cathode life is limited by the buildup of foreign material, through cryopumping, on the cathode surface. To obtain practical operating lifetimes at LN_2 temperature, it was necessary to add surfaces cooled to this temperature over much of the interior region of the gun structure. This is the only significant change in the source from the description given in ref. 2. With the LN_2 cooled surfaces in place, cathode lifetimes at low temperature ranged between several hours and 64 hours. We found it possible to restore the cathode quantum efficiency to near its original value by briefly elevating the cathode temperature to between -100 °C and -40 °C to desorb the cryopumped gases. This operation could be repeated a number of times before it was necessary to completely reform the cathode by heat cleaning and re-cesiation. As our source had two independent polarized guns, one could be delivering beam while the other was being reprocessed. Given the much longer cathode lifetimes obtained with room temperature operation, there is a considerable operational premium in finding either operating conditions or cathode materials which will deliver high polarization at room temperature.

VERY HIGH CURRENT PHOTOCATHODES

As noted earlier, we observed that very large photocurrents could be delivered by GaAs photocathodes. Theoretically, it should be possible to extract photocurrents of hundreds of amperes per cm^2 from such cathodes before any limiting phenomena set in. Furthermore, one expects that the emitted electron current should follow the incident optical pulse shape into the sub-nanosecond pulse width regime.

To measure the high current and short pulse behavior of GaAs photocathodes, we designed the test setup shown in figure 1. This small ultrahigh vacuum chamber was designed to allow us to prepare cathode surfaces and measure the magnitude and time structure of the beam current only, without making any beam polarization measurements. With a 50 kV interelectrode voltage, the gun was space charge limited with about 50 A of beam current. Beam current was measured in two ways: with a capacitively decoupled 1 ohm resistor in series with the cathode, and with a Faraday cup beam dump. The Faraday cup was constructed to form a 5 ohm coaxial line inside a snout on the vacuum chamber. Beam currents were observed with a 400 MHz real time oscilloscope. The system was calibrated by allowing the Faraday cup current to charge a known capacitor. A solenoid of up to 2×10^4 amp-turns strength covered the region between the anode and the entrance to the Faraday cup. The optical pulse was produced by rapidly pulsing a Pockels cell placed between crossed polarizers and located in the output beam of a frequency doubled Nd:YAG laser.

Test results with this gun showed a beam current of 60 A leaving the cathode, of which 30 A were detected in the Faraday cup, at a gun voltage of 57 kV. The electron pulse shape was observed to follow the optical pulse shape, as measured by a fast photodiode, into the 1.5 to 2 nsec regime, the fastest which could be reliably observed with our 400 MHz oscilloscope. The illuminated area for these measurements was 6 mm in diameter, giving a peak current of 180 A/cm^2, considerably greater than currents obtainable with conventional thermionic emitters. It is worth noting that these short pulses are obtained without the use of a grid, giving a better emittance than is possible with gridded structures.

The quantum efficiency of the cathode was measured with both a 2 mW He-Ne laser, and an 80 kW pulse from the doubled Nd:YAG laser. Within the precision of the measurements, about 25%, the quantum efficiencies were the same, indicating that no limiting mechanism is occurring in the GaAs over a range of 4 x 10^7 in incident optical power. With 57 kV on the gun, the field at the cathode is 80 kV/cm, much greater than the 13 kV/cm used on the cathodes for the parity experiment. This demonstrates that cesiated cathodes can be operated in these high fields without breakdown. No cathode deterioration was observed during these tests, although they were of far shorter duration than the actual running time accumulated on the cathodes used in the parity experiment.

On the strength of these results, we are developing a high current, short pulse polarized electron gun as a prototype for use on the linear collider 3. We expect to be able to deliver 5 x 10^{10} electrons into a single S-band bunch. Space charge effects dictate that we sub-harmonically bunch the gun beam pulse before entering the S-band structure. As a consequence, this developmental gun will not have to perform at the levels achieved in the tests described above. The gun will operate at a nominal 200 kV, and will be space charge limited at 15 amperes. Initial operation will be unpolarized, to simply test the acceleration and behavior of intense single bunches in the linac. At the time of writing this paper, the gun structure is completed and undergoing initial vacuum tests.

HIGHER POLARIZATION PHOTOCATHODES

The maximum polarization obtainable from a GaAs photocathode is limited by the degeneracy at the top of the valence band to 50%. To increase this polarization, some means must be found to remove this degeneracy. We are investigating several ways to accomplish this, including: (1) application of a uniaxial stress to GaAs; (2) use of GaAs-GaAlAs multilayer structures; and (3) use of II-IV-V$_2$chalcopyrite semiconductors.

A. Uniaxially stressed GaAs

The degeneracy at the top of the GaAs valence band can be removed by the application of a uniaxial stress to the crystal. The valence band splitting obtained is a few meV per kbar of applied stress. Not only does it seem very difficult to engineer a stressed cathode, but the small size of the splittings imply that, if successful, the method would be useful only for relatively low photocurrents because of the need to operate very near the bandedge. We are studying the polarization of electrons optically pumped to the conduction band in stressed GaAs by observing the polarization of the recombination photoluminescence. Application of this technique to polarized electron sources seems a long way off.

B. Multilayer GaAs-GaAlAs structures

A group at Bell Laboratories has grown, by molecular beam epitaxy, semiconductor structures composed of alternating layers of GaAs and GaAlAs 4. Each layer is several tens of Angstroms thick, and the entire structure is some 10^4 Angstroms thick. This structure effectively produces a one dimensional square well modulation on the bandgap energy near the bandgap minimum, and removes the degeneracy as desired. By measuring the polarization of the luminescence excited by circularly polarized light, the Bell group has inferred a conduction band electron polarization greater than 80% 4. This group has supplied samples for our evaluation as polarized electron emitters.

We have successfully prepared photocathodes on these structures, and have measured emitted electron polarizations. The results are encouraging, though we have yet to achieve the high polarizations expected. Two features make our results difficult to interpret. The first is that the material provided is not just the simple multilayer structure described above. The actual multilayer is grown on a layer of epitaxially grown GaAs, which in turn is grown on a GaAs wafer of lower quality. A p-doped GaAs cap layer is grown on top of the multilayer region to facilitate cathode preparation. Thus the emitted electrons may originate from a considerable body of material other than the multilayer structure. A second complication arises from our method of surface cleaning prior to cathode preparation. We typically heat the photocathode material to a high temperature (≃ 650 °C) for 15 minutes as a cleaning method before adding cesium to activate the cathode. This high temperature treatment can cause diffusion of the aluminum in the material, damaging the "one dimensional square well" modulation of the bandgap energy.

We have measured photoemitted beam polarization from a number of the Bell Laboratory samples. Some early results are shown in figure 2. The maximum polarization appears at the wavelength expected from photoluminescence measurements on the same sample. The enhancement in the polarization was small but reproducible, and appeared at room temperature as well as at LN_2 temperature.

The Bell Laboratory group pointed out to us that if the enhanced polarization arises from the multilayer region of the sample, it should have an associated increase in the quantum efficiency. We observe this behavior. If we use our results for the quantum efficiency and polarization from this sample, and model the result as being due to a contribution from a GaAs-like polarization of 44% and a contribution from the multilayer of unknown polarization and magnitude given by the increase in the quantum efficiency, our results are consistent with a small (≃10 - 15%) contribution of about 85% polarization from the multilayer.

With this result, we felt that it was likely that the majority of the photoelectrons were originating in the p-doped GaAs cap layer, rather than the multilayer region. We have therefore removed this cap layer in small amounts, measuring the polarization obtained as the layer is thinned. A result is shown in figure 3. The thinner cap layer gives a consistently high polarization, but any narrow structures in the polarization are washed out. This may well be due to the aluminum diffusion problem noted above. Each new measurement involved a new cathode preparation, and thus further treatment at high temperature, aggravating this problem. We currently have the sample of figure 3 with a cap layer thinned to 200 Angstroms ready for polarization measurement. Bell Laboratory is preparing new samples for us, designed to avoid the cap layer problem. The highest polarization we have measured from samples of this type, 53%, is not the high polarization hoped for, but it represents a significant improvement over ordinary GaAs, and the difficulties with the method may well be solved with different samples.

C. II-IV-V_2 chalcopyrite semiconductors

Intellectually, perhaps the best way to make a high polarization photocathode is to employ a material which already has the desired band structure, rather than try to alter the GaAs band structure by stress or the use of artificial structures. Materials with the desired band structure exist in nature, but are not generally available. One such class of materials is the II-IV-V_2 chalcopyrite semiconductors. These materials have a tetragonal structure, rather than the cubic structure of GaAs, and the crystal field is responsible for removing the degeneracy.

Some time ago, we concluded that $CdSiAs_2$ was the most favorable of these materials for polarized electron work, and were able to obtain very small samples of this material grown by the Bridgeman method. The material was found to grow peritectically, making a lengthy study necessary before large samples could be expected. The small samples we obtained were not suitable for cathode preparation studies.

Recently, Zurcher and Meier at ETH have studied the II-IV-V_2 compounds as possible polarized electron emitters 5. They worked with $ZnSiAs_2$ and $ZnGeAs_2$. They measured a polarization of 50% from $ZnSiAs_2$, but as they pointed out, the band structure of this material is not well suited to a high polarization emitter. The $ZnGeAs_2$ sample had an appropriate band structure, but a bandgap so small that a negative affinity cathode surface could not be prepared. Their studies were limited by small sample size and poor sample availability.

Very recently, we have been able to obtain very large (2 cm. diameter) samples of $ZnSiAs_2$ of excellent crystalline quality, grown by the metal organic chemical vapor deposition technique 6. We have successfully prepared cathodes on this material with a quantum efficiency an order of magnitude greater than that reported in ref. 5. As the difficulty with the $ZnSiAs_2$ band structure is with the conduction band, rather than in the valence band as for GaAs, we believe that it may be possible to obtain high polarization from this material by activating with rubidium or potassium, rather than cesium, to obtain a work function which will preclude photoemission from the undesired conduction band levels. Experiments to test this idea are underway.

Perhaps the most interesting aspect of the availability of large, high quality samples of $ZnSiAs_2$, is that it may be possible to grow samples of similar size and quality of the closely related compound $CdSiAs_2$. SLAC is supporting work to test this idea. Without going into a flurry of band structure and solid state physics discussion likely unfamiliar to most high energy physicists, let me close with the optimistic note that the GaAs photocathode was the first such photoemission cathode to be designed on paper before its experimental realization 7. Perhaps $CdSiAs_2$ will prove to occupy the same place for polarized photoemitters.

ACKNOWLEDGMENTS

Edward Garwin, Roger Miller, and Charles Prescott of SLAC have joined on various aspects of the work reported here. Art Gossard and Robert Miller of Bell Laboratories have been very helpful in supplying the multilayer samples, and in interpreting our results. Finally, J. E. Andrews of the Research Triangle Institute has supplied the $ZnSiAs_2$ samples, and is developing growth techniques for $CdSiAs_2$.

REFERENCES

1. C. Y. Prescott et al., Phys. Lett. 77B, 347 (1978); and Phys. Lett. 84B, 524 (1979).
2. C. K. Sinclair et al., in High Energy Physics With Polarized Beams And Targets, A.I.P. Conf. Proc. No. 35, 1976, 424.
3. SLAC Linear Collider Conceptual Design Report, SLAC Report No. 229, unpublished.

4. R. C. Miller et al., Phys Rev. B21, 1569 (1980); and Phys. Rev. B22, 863 (1980).
5. P. Zurcher and F. Meier, J . Appl. Phys. 50 3687 (1979).
6. J. E. Andrews, private communication.
7. J. J. Sheer and J. van Laar, Solid State Comm. 3, 189 (1965).

*Work supported by the Department of Energy under Contract DE-AC03-76SF00515.

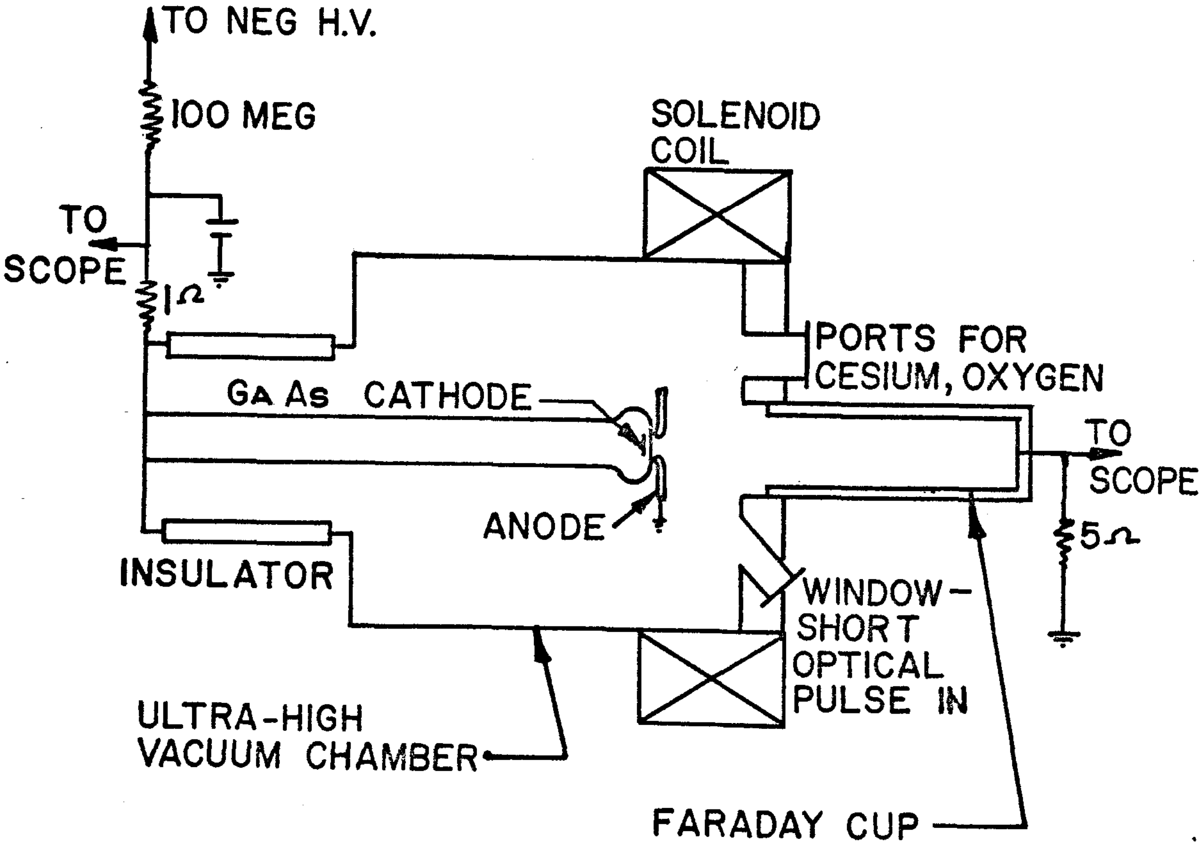

Figure 1. Schematic of the test chamber for the study of high current, short pulse, GaAs cathode behavior.

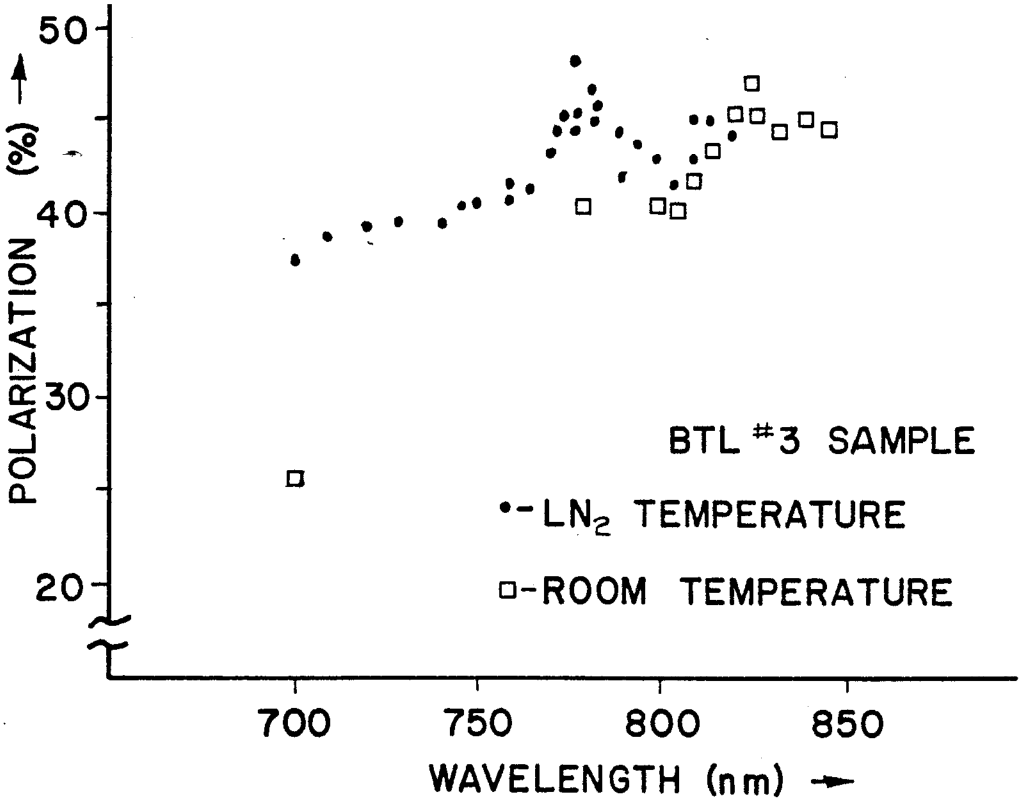

Figure 2. Polarization measured from a Bell Labs multilayer sample, showing a small polarization enhancement.

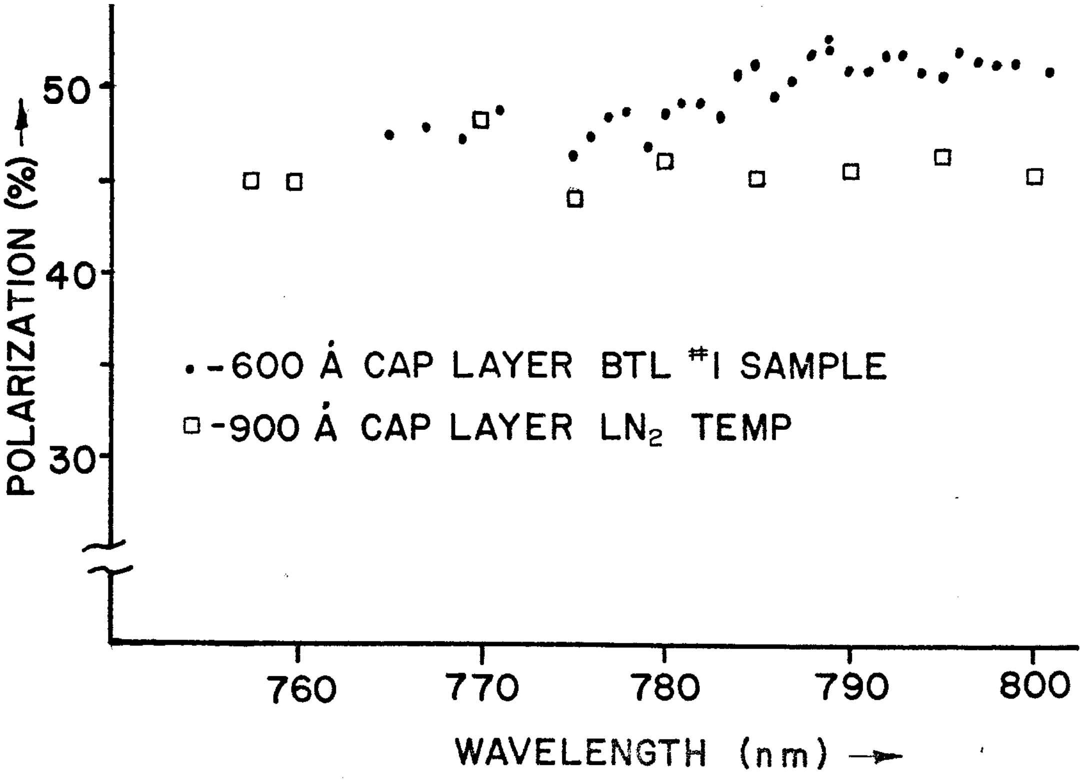

Figure 3. Increased polarization observed as the cap layer is removed.