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Development of Polarized Photocathodes for the Linear Collider

Accelerator Physics - Year 1 of Continuing Proposal

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Proposal to the University Consortium for a Linear Collider

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Proposal Name

Development of Polarized Photocathodes for the Linear Collider

Classification

Accelerator (New Proposal)

Personnel and Institution requesting funding

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Project Overview

The development of high current polarized photocathodes is very important for the Linear Collider (LC) project. Physics requirements call for highly polarized electron beams with a goal of at least 90% polarization.

A Wisconsin-SLAC collaboration has been developing and studying polarized photocathodes which have been used for the SLAC SLD and fixed target programs. A more recent goal is the development of photocathodes with a polarization in excess of 90% which meet the NLC charge requirements. This work started as a SLAC-Wisconsin collaboration (E. Garwin, T. Maruyama of SLAC and R. Prepost of Wisconsin) and has evolved into a formal SLAC collaboration called the Polarized Photocathode Research Collaboration (PPRC).

SLAC personnel now also include J. Clendenin, R. Kirby, D. Luh, A. Brachmann, and S. Harvey

To date, well over 80% polarization has been achieved with strained gallium arsenide photocathodes which have been used in past SLAC experiments. The 1994-1998 SLC operation with the SLD detector and subsequent fixed target experiments E-142, E-143, E-154, E-155, and E-155X used strained gallium arsenide cathodes which produced at least 80% polarization at the source. More recently, a newly developed high current polarized photocathode used for SLAC experiment E-158 achieved a polarization of about 85% with a charge approaching that required for the NLC.

These applications were the world's first use of strained photocathodes specifically designed for a polarized electron source, resulting in record polarization for a high intensity electron linac. The research and development program will continue to focus on studying the properties of these cathodes with respect to spin relaxation, quantum efficiency, and charge saturation, with the goal of developing photocathodes for use with the LC.

Early research efforts focused on the development of strained photocathodes since electron spin polarization higher than 50%, approaching 100%, is theoretically possible using cathode structures which have less crystal symmetry than unstrained GaAs. As long as GaAs or any zinc blende type structure is used for cathodes, the electron polarization is limited to $\leq$50% due to the degeneracy of the valence bands.

Since the seminal studies with strained InGaAs, research has been carried out with strained GaAs epitaxial layers grown on a GaAsP buffer layer. Electron spin polarizations approaching 85% were observed at low quantum efficiency (QE), decreasing to about 80% at high QE. A variety of layer thicknesses and strains were studied using MOCVD grown samples commercially obtained from the SPIRE Corporation in Bedford, MA. The samples were of high quality, and all samples studied to date have shown a significant polarization enhancement in excess of the unstrained maximum polarization of 50%. The epitaxial layer thicknesses varied from 0.1 μm to 0.3 μm and the strains of approximately 1% resulted from phosphorous concentrations ranging from 21% to 28%. Even the 0.3 μm thick sample, well in excess of theoretical estimates for the critical thickness for pseudomorphic growth, reached an electron spin polarization of 75% at low QE and 70% at high QE, demonstrating significant persistance of lattice strain.

We have continued R&D efforts on cathode structures to address certain issues, specifically 1) fundamental properties of materials, 2) higher polarization, and 3) higher charge limit. The cathode charge limit, was not a limiting factor for the SLAC SLD and fixed target programs but is an issue for a LC polarized source with an NLC micro-bunch structure. The LC with an NLC micro-bunch structure requires higher peak current than can be obtained from the photocathodes that were used for the SLAC SLC program. Provided that the photocathode output charge is not limited by the space charge limit of the electron gun, the output charge is limited by charge saturation of the photocathode itself. Charge saturation occurs because a photovoltage develops at the cathode surface at high currents acting as a potential barrier for further charge emission

One possible cure for this problem is to increase the p-type doping in the epitaxial surface layer. Over the past two years systematic studies have been made of strained GaAs samples where the electron polarization was measured as a function of the high doped surface layer thickness. The results showed, as expected, that the polarization increases as the high doped layer thickness is reduced. From these studies it was concluded that greater than 80% polarization could be obtained with about 5-10 nm of a surface layer doping of 5×10^{19} cm^{-3}.

High surface layer doped samples have been grown to our specifications by the Bandwidth Semiconductor Corporation (former SPIRE Corporation). The basic structure was a 0.1 μ GaAs active layer highly doped for the first 10 nm of surface and strained by a GaAsP buffer layer. The highly doped surface layer is kept very thin so as not to decrease the electron polarization. The high doping surface layer has the effect of decreasing the band gap near the surface, resulting in a small potential barrier. A small amount of phosphorus (5%) was added to the active layer to compensate the energy difference in the conduction band resulting from the high gradient doping.

This structure was tested with a long pulse laser system to simulate the NLC 190 microbunch train of total length 266 ns. The NLC charge requirement for the source is 2.2 nC in each microbunch for a total of 420 nC, about 25 times the SLC maximum charge. A short YAG-Ti laser pulse was superimposed on the long flash-Ti laser pulse to simulate the peak charge requirement of a single microbunch. The resultant measurements of extracted charge vs laser energy showed no charge saturation up to the maximum laser energy. Both the microbunch peak charge and the total charge of the macrobunch nominally approach the NLC charge requirements. This new cathode structure was used for the first two runs (2002) of the fixed-target experiment E-158 which required about 80 nC in a 300 ns pulse, a higher charge requirement than previous cathodes have been able to deliver. The electron polarization was in excess of 80%, in accord with polarization measurements measured in the test lab.

Another approach to obtain higher photocathode output charge is to increase the thickness of the photocathode active layer, ordinarily limited to about 0.1 μ. Larger thickness of the active layer results in serious degradation of the strain. Superlattice structures can in principle overcome the inherent thickness limitation of single heterostructures. Molecular Beam Epitaxy (MBE) superlattice structures have been grown for us by SVT Associates through an SBIR award with SLAC as the technical partner. Measurements of these structures during 2002-2003 have shown both good QE and high polarization. These measurements are continuing during 2003-04 with the goal of fine-tuning the superlattice parameters. To this date, peak polarizations of 85% and QEs of about 1% have been achieved. Fig. 1 shows polarization and QE vs. laser wavelength for several different SVT photocathode structures with varying superlattice parameters. The peak polarizations and QE are consistent with superlattice computer simulations. The superlattice structures shown here are typically 16 periods of 3-4 nm $\mathrm{GaAs_{1-x}P_x}$ barriers alternating with 3-4 nm GaAs wells with a phosphorus fraction of $\mathrm{x} = 0.35$. The extracted charge nominally meets NLC peak charge requirements. One of these superlattice photocathodes was used successfully for the final run of E-158 in 2003.

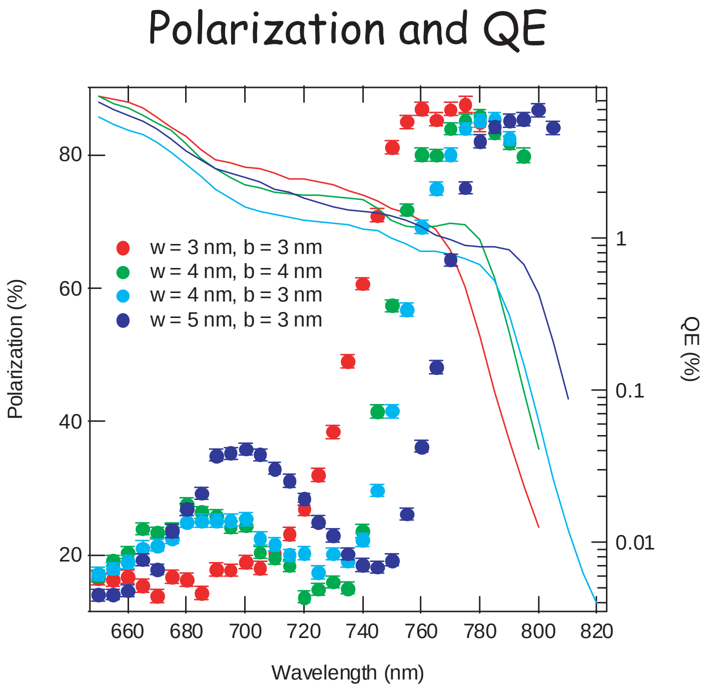

Figure 1: Polarization and QE for several SVT GaAsP/GaAs superlattice samples vs. laser excitation wavelength. Here w is the well width and b is the barrier width.

Another problem which has been addressed during 2003 is the dopant loss and strain relaxation during the relatively high temperatures used for heat-cleaning. This factor tends to prevent the achievement of ultimate performance from the photocathodes. To this end we have tested an atomic hydrogen cleaning system based on a Jefferson Lab design. The goal of atomic hydrogen cleaning is to achieve high QE using a heat cleaning temperature of 450°C. This temperature is in contrast to the normal heat cleaning temperature of 600°C which results in the degradation effects mentioned above. Our studies have shown that when hydrogen ions are prevented from reaching the photocathode, the performance goals are achieved.

Description of Project Activities

The research and development program divides into several well defined parts as follows:

1. **Fabrication**

   The cathode structures are grown by a commercial or academic partner who has the facilities required for structure growth. Currently we receive structures from SVT Associates with whom SLAC currently has a Phase II SBIR award, now in the final year, and from a Russian group at St. Petersburg Technical University with whom SLAC shares a CRDF grant.

2. **Photocathode Characterization**
   The parameters of the photocathodes must be measured, requiring a variety of techniques including, but not limited to, X-Ray Bragg measurements, Electron Microscopy, Secondary Ion Mass Spectroscopy (SIMS), Auger analysis and Photoluminescence measurements.

3. **Measurement of Polarization, Quantum Efficiency (QE), and Charge Limits**
   SLAC has the facilities for these measurements using a cathode test system (CTS) for measurements of polarization and QE, and a HV gun test lab for measurement of charge saturation properties.

4. **Structure Design**
   The design of a photocathode structure requires computer programs to calculate the parameters for a band structure which calculations show have the desired polarization and charge. The analysis of X-Ray curves also requires X-Ray simulation software.

Results of Prior Support

The proposal submitted in Oct. 2003 was approved for funding on Oct. 2004. Since the funding has only recently been received, no actual funds have been expended, but quotations for specific superlattice cathodes structure from SVT Associates were requested and received on Feb. 2, 2005. As described below, the research is focussed on producing photocathodes which have polarization in excess of 90% and a peak output charge meeting the charge requirements of the ILC. The technical decision for the superconducting structure has no impact on the R&D for the polarized photocathode stuctures.

The research to date has been successful in achieving higher polarization and higher QE, but the goal of $> 90\%$ polarization has not been achieved. The polarization appears saturated at 85% and a material-specific spin-depolarization mechanism appears to be present. To address material-specific spin depolarization mechanisms and and achieve higher polarization, we propose to develop a strained superlattice based on GaAs and InGaP. A GaAs/InGaP superlattice structure differs from the previously studied GaAs/GaAsP superlattice structure in that GaAsP superlattice barrier layers are replaced by InGaP. The GaAs strained wells remain the same.

The new strained superlattice is expected to increase the polarization because the spin relaxation rate in InGaP is less than in GaAsP. Since the band-gap energy of InGaP is larger than that of GaAsP, an enhancement of the Quantum Efficiency is also expected.

Project Activities and Deliverables–FY2004-2006

Research will continue with the goal of producing photocathodes which have polarization in excess of 90% and a peak output charge meeting the charge requirements of a LC with the microbunch structure of the NLC LC. Some of the structures studied to date are excellent candidates for meeting these requirements. The current research is with superlattice structures. Superlattice structures are particularly difficult to design since there are many parameters, making it difficult to simultaneously optimize QE and polarization. The target parameters for a structure are not always met during the fabrication process, making it very important to have many samples and high quality characterization techniques. One of the key studies is how to achieve maximum possible polarization while still satisfying the peak charge requirements.

Work will also continue with studies of atomic hydrogen cathode cleaning which results in being able to use lower heat cleaning temperatures. Lower heat cleaning temperatures result in lower dopant loss, dopant diffusion, and strain relaxation. We propose to build a hydrogen cleaning system with a load-lock system which will enable the transfer of cathodes between test systems.

Budget Justification

We propose a budget for the following items:

1. **Purchase of photocathode structures from a commercial source** The commercial source is presently SVT Associates which has the facilities for MBE growth with Be doping. The request for each FY is for 5 cathode structures @ 3K$ each, representing about 1/2 of the research requirements.

2. **Facility Upgrade** We plan to upgrade the photoluminescence facility which Robin Mair, a former Wisconsin student, used for his PhD work on the study of strained photocathodes. The photoluminescence facility has proven to be very valuable for structure characterization. The photocathode structures discussed above require an expanded wavelength range which will be accomplished by obtaining more diode laser heads. The request is for two laser heads for year 1 with a similar amount for additional photoluminescence diagnostic equipment in years 2 and 3.

3. **Characterization Studies** X-Ray and SIMS analyses are done off-site and payment is required. We have in the past done X-Ray analyses at Wisconsin and currently use a facility on the Stanford campus. We run the analyses but pay to use the facility. SIMS analyses are done by a commercial vendor. SIMS analyses measure the doping profile of the samples. The request is for 1/2 of the anticipated research needs.

4. **Travel** The travel request is for 1/2 of the Prepost trips to SLAC.

Budget (K$)

Item	FY2004	FY2005	FY2006
Cathodes	15	15	15
X-Ray Analyses	5	5	5
SIMS Analyses	3.6	3.6	3.6
Laser Heads	3	0	0
Diagnostic Equipment	0	3	3
Travel	5	5	5
Total Direct Costs	31.6	31.6	31.6
Indirect Costs	3.0	3.0	3.0
Total	34.6	34.6	34.6

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