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DEVELOPMENT OF SPIN POLARIZED ELECTRON SOURCES BASED ON III-V SEMICONDUCTORS AT BNL*

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Abstract

Photocathodes capable of producing spin polarized electrons beams are required for both high energy and nuclear physics experiments. In this work, we describe in detail the commissioning of a new apparatus for photocathode characterization, which includes a retarding field Mott polarimeter for the measurement of electron spin polarization. We illustrate the design of superlattice structures equipped with Distributed Bragg Reflector and present the measurements of electron spin polarization and quantum efficiency of emitted electrons from these structures.

INTRODUCTION

The use of spin polarized electron source finds application in a wide range of electron accelerators of interest for High Energy Physics. The planned International Linear Collider [1] is designed to collide spin-polarized electrons and positrons at very large energies in the TeV scale, SuperKEKB is considering upgrading to a highly spin-polarized electron source [2]. These facilities are projected to require a relatively modest amount of average current, not more than few hundreds of μA that can be produced by state-of-the-art photoelectron sources equipped with GaAs-based photocathodes. On the other hand, facilities like the Large Hadron Electron Collider [3] are planning to operate with very high average electron beam currents, tens of mA, which are well beyond the current state-of-the-art. Furthermore, the need to develop sources capable of providing highly spin-polarized electrons with high average beam currents will enable the realization of spin polarized positron beams for future colliders. The recent demonstration of efficient transfer of the high spin polarization from electrons to positrons via a two-step process has triggered increasing interest in the realization of such source. In the first step polarized bremsstrahlung radiation is generated by a polarized electron beam in a high-Z target; in the second step this polarized bremsstrahlung radiation produces polarized positrons by pair-production process in the same target [4]. Given the relatively low efficiency of the process of production and subsequent capture of the positron beam (10^{-4}-10^{-3}) there is a need for developing electron sources that can produce tens of mA of average spin-polarized beam current to support the production of polarized positrons in the μA range.

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EXPERIMENT AND RESULTS

Experimental Setup

To perform dedicated studies aimed at the development of advanced photocathodes based on III-V semiconductors to produce highly spin polarized electron beams we assembled a dedicated UHV experimental chamber that allows for the activation of photocathodes to Negative Electron Affinity (NEA) and the measure of their QE and ESP.

The UHV system consist of three vacuum chambers: the load lock, the activation chamber and the Mott polarimeter chamber. A combination of ion pumps and Ti sublimation pumps allows the vacuum system to operate in few 10^{-11} Torr.

The load lock is isolated with a gate valve from the other vacuum chambers allowing us to exchange samples without breaking the vacuum of the activation and polarimeter vacuum chambers. The exchange requires about 24 hours as we perform a short bake out cycle to remove water vapors.

The activation chamber hosts the sample holder used during activation and characterization of the samples. The holder is equipped with a Boron Nitride heater capable of bringing the samples to temperatures above 600 C. Samples can be negatively biased and a calibrated K Type thermocouple is used to measure the temperature of the sample. Cesium vapors from a metal chromate dispenser and high purity oxygen coming from a leak valve are used to perform the NEA activation of the samples using the well known "yo-yo" method.

The retarding field Mott polarimeter is operated with an Au target maintained at a voltage of 25 kV. It allows operation with up to 4 channeltron detectors for measuring the electron spin polarization. As the electrons produced in our experiment from III-V semiconductors have the spin direction perpendicular to the sample surface only two channeltrons are needed to measure the ESP. Additional details about this retarding field Mott polarimeter can be found in Ref. [5].

The read-out of the channeltrons signals is performed using two pulse preamplifiers with high voltage decoupling network that bias the channeltrons and apply a threshold to the measured signal. The TTL outputs pulses produced by the preamplifier are detected using a digital counter connected to a PC running a dedicated Labview interface.

The photons used to illuminate the photocathode during the photoemission experiments are produced by a tungsten halogen lamp (Oriel model 66088) coupled with a monochro-

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mator (Oriel Cornerstone 130) are used as the source of light for the measurement. The monochromator is used to select the central emission wavelength with bandwidth of about 10 nm. A combination of a linear polarizer (Thorlabs LPVIS050) and a tunable liquid crystal retarder (Thorlabs LC1113B) is used to produce the left- and right-handed circularly polarized light required to produce spin polarized electrons.

GaAs	5 nm	p = 5x10^{19} cm^{-3}	
$GaAs_{0.62}P_{0.38}$	4 nm	p = 5x10^{17} cm^{-3}	30 pairs
GaAs	4 nm	p = 5x10^{17} cm^{-3}	
$GaAs_{0.81}P_{0.19}$	300 nm	p = 5x10^{18} cm^{-3}	
$AlAs_{0.78}P_{0.22}$	65 nm	p = 5x10^{18} cm^{-3}	10 pairs
$GaAs_{0.81}P_{0.19}$	55 nm	p = 5x10^{18} cm^{-3}	
$GaAs_{0.81}P_{0.19}$	2000 nm	p = 5x10^{18} cm^{-3}	
GaAs->$GaAs_{0.81}P_{0.19}$	2750 nm	p = 5x10^{18} cm^{-3}	
GaAs buffer	200 nm	p = 5x10^{18} cm^{-3}	
GaAs substrate		p > 1x10^{18} cm^{-3}	

Figure 1: Schematic of the superlattice GaAs photocathode with DBR structure. The GaAs surface layer was capped with amorphous As after the epitaxial growth.

Design and Growth of Photocathode Structures

The photocathode structures were designed with strain compensated superlattice with the intent of growing a large number of well and barrier pairs that could produce electrons with high spin polarization with high QE [6]. The photocathode structure consists of 84 layers and a schematics of the layer arrangement is reported in Fig. 1.

Photocathode structures were grown at Sandia National Laboratories using Molecular Beam Epitaxy (MBE) on a p-type ($> 1 \times 10^{18}$ cm^{-3}) (100) GaAs wafer (lattice constant = 5.653 Å). A 200 nm buffer layer of p-type ($> 5 \times 10^{18}$ cm^{-3}) GaAs was used to regrow the GaAs surface and provide a flat surface. Over the GaAs buffer, a graded composition layer from GaAs to $GaAs_{0.81}P_{0.19}$ with a thickness of about 2750 nm with p-type doping ($> 5 \times 10^{18}$ cm^{-3}) was used to slowly decrease the lattice constant of the surface to 5.614 Å. Around 2000 nm of $GaAs_{0.81}P_{0.19}$ was grown on top of that as a virtual substrate for the Distributed Bragg Reflector structure. The DBR consists of $AlAs_{0.78}P_{0.22}$ and $GaAs_{0.81}P_{0.19}$ layers with a nominal thickness of 65 and 55 nm, respectively. A nominally 300 nm thick tuning layer is grown to provide the optical thickness for the tuning of the Fabry–Pérot resonator. The strain compensated (-0.7%, +0.7%) SL structure consists of 30 pairs of p-type (5×10^{17} cm^{-3}) $GaAs_{0.62}P_{0.38}$/GaAs (4/4 nm thickness). The structure is terminated with a 5 nm highly p-doped (carbon doping of 5×10^{19} cm^{-3}) GaAs layer. Before extracting the sample from the MBE reactor wafers are capped with a thick arsenic layer that prevents the formation of oxide on the GaAs surface.

Photocathode Activation and QE

A sample of about 10x10 mm^2 was produced by cleaving of central part of the photocathode wafer. The sample was loaded into the load-lock and after a 24 hour bake-out at 150 C it was moved into the activation chamber. Here, a two hours heat cleaning of the sample was performed at a temperature of about 450 C to remove As capping layer and other contaminants. Once the sample was cooled to room temperature, a "yo-yo" activation process was performed with cesium vapors and oxygen gas to generate a NEA condition. A 532 nm diode laser is used to illuminate the negatively biased (-20 V) photocathode during the Cs-O activation and the photocurrent is recorded with a picoammeter (Keithley Model 2400). At each cycle of the activation procedure, the surface of the photocathode is over exposed to cesium vapor. The over exposure is controlled by having the emitted photocurrent to exceed the peak value and drop to ~ 65% of the peak value at every cycle. Similarly, the over exposure to the oxygen flux is controlled by having the emitted photocurrent to exceed the peak value and drop to ~ 80% of the peak value at every cycle.

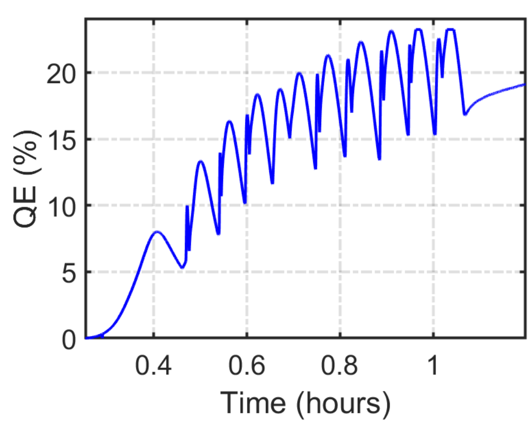

Figure 2: Temporal evolution of QE during the cesium and oxygen "yo-yo" activation process of the GaAs/GaAsP superlattice with DBR photocathode.

The Cs and O_2 cycles are repeated until a plateau is observed in the temporal evolution of photocurrent. The activation is terminated by depositing a layer of Cs until the photocurrent drops to ~ 80% of the peak value. Figure 2 shows the temporal evolution of quantum efficiency (QE) from the investigated superlattice sample structure during a yo-yo activation with Cs and O_2. A peak QE of ~ 24 % was achieved at 532 nm during the activation process. The final QE at the end of activation cycle was ~ 19 %.

The NEA activation is followed by the measurement of spectral response of the activated superlattice structure using the light produced from the lamp and monochromator. Figure 3 shows the QE of the cathode over wavelengths rang-

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ing between 700 and 820 nm. A peak QE of ~ 18% in this spectral range is measured at 780 nm.

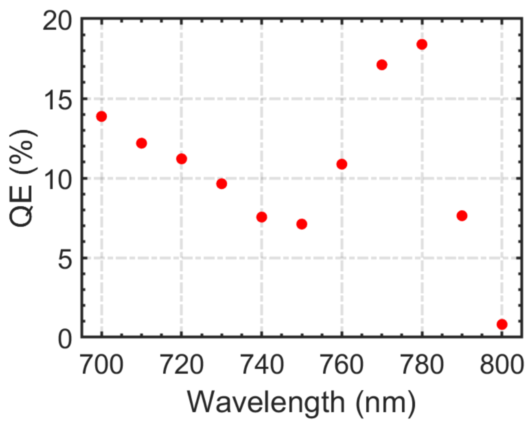

Figure 3: Measured spectral response of the GaAs/GaAsP superlattice with DBR photocathode. A maximum QE of ~ 18% was observed at 780 nm.

Electron Spin Polarization

The electrons emitted from the cathode on illumination with circularly polarized light just above band gap energies, are longitudinally spin-polarized. In order to measure the ESP in the retarding Mott electrons must be transported and hit the Au target with their spin oriented parallel to the target surface. To achieve this the Mott detector is equipped with a series of electrodes that allow to transport the electron only using electric fields so that the spin of electrons is not perturbed. The transport of the electrons from the photocathode to the Mott target has been simulated using the SIMION electron optics package [7]. Fine tuning of the potential applied to the electrodes was performed with the electron beam to optimize the transport efficiency. Figure 4 shows the trajectories of electrons as obtained from the SIMION model. A maximum transport efficiency of ~ 25 % has been achieved between the photocathode and the Mott target.

With the photocathode negatively biased at -140 V with respect to the vacuum chamber photoelectrons were transported to the Mott scattering target which was biased at 25 kV. From the measured asymmetry in the counts of the channeltrons and assuming an effective Sherman function for our system of 0.13, as calibrated using a bulk GaAs sample, we estimated the ESP as function of the exciting wavelength. Figure 5 shows the measured ESP from the GaAs/GaAsP superlattice with DBR structure. A maximum ESP of ~ 90% was observed at λ = 790 nm.

CONCLUSION

In summary, a retarding field Mott polarimeter was commisioned at Brookhaven National Laboratory. GaAs/GaAsP superlattice with DBR photocathode have been designed and fabricated using MBE technique at Sandia National Laboratories. Using this photocathode structure, a peak QE of ~ 18% at 780 nm and a ESP of ~ 90% were attained at 790 nm.

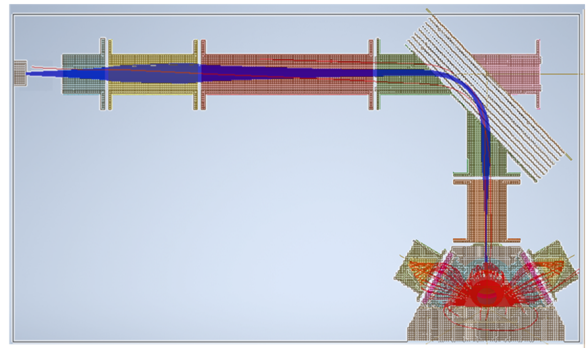

Figure 4: SIMION electron beam tracking simulations have been performed to optimize the electrostatic transport of electrons from the cathode to the the target (trajectories in blue) and from the target to the channeltrons (trajectories in red).

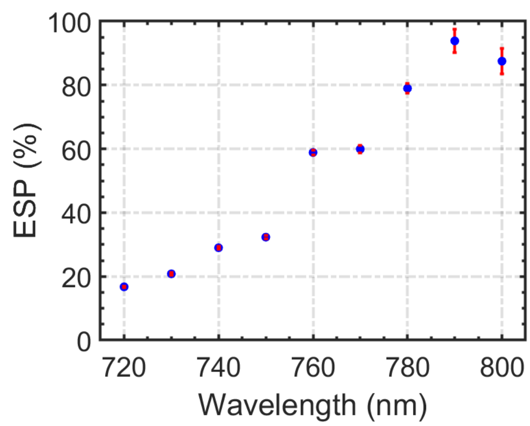

Figure 5: ESP as funtion of the illuminating wavelength as measured for the GaAs/GaAsP superlattice with DBR photocathode in the wavelength range between 720 and 800 nm.

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