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QUEST FOR AN OPTIMAL SPIN-POLARIZED ELECTRON SOURCE FOR THE ELECTRON-ION COLLIDER *

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Abstract

Superlattice GaAs photocathodes play a crucial role as the primary source of polarized electrons in various accelerator facilities, including the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson National Laboratory and the Electron-Ion Collider (EIC) at Brookhaven National Laboratory. To increase the quantum efficiency (QE) of GaAs/GaAsP superlattice photocathodes, a Distributed Bragg Reflector (DBR) is grown underneath using metal-organic chemical vapor deposition (MOCVD). There are several challenges associated with DBR photocathodes: the resonance peak may not align with the emission threshold of around 780 nm, non-uniform doping density in the top 5 nm may significantly impact QE and spin polarization, high-temperature heat treatment may lead to interlayer material diffusion, and the number of DBR pairs may not be optimal, affecting both QE and spin polarization. In this paper, we will report our progress in addressing these challenges to hunt for suitable photocathodes for the EIC.

INTRODUCTION

Polarized electron sources are essential in fundamental research across multiple disciplines, such as condensed matter physics and elementary particle physics. Polarized electron sources are utilized in polarized electron microscopes to probe domain walls in ferromagnetic materials. The Electron-Ion Collider (EIC) requires a polarized electron beam with 7 nC of initial bunch charge and spin polarization of at least 85% from the source. The maximum polarization from bulk GaAs, is about 35-40% due to the degeneracy of the heavy-hole, and light-hole at the $2p_{3/2}$ band state and spin relaxation. GaAs/GaAsP-based superlattice layer can eliminate the degeneracy in the $2p_{3/2}$ band state, thus spin-polarized electrons can be extracted from one of the bands. Electron spin polarization of around 92% is reported previously, however, the QE lies around 1% or lower at near band gap photon energies [1, 2].

A distributed Bragg reflector (DBR) grown underneath the superlattice layer with a buffer layer can effectively trap the light and enhance the photon absorption which in turn increases the quantum efficiency (QE). Such a structure demonstrated record performances achieving ESP of 84% and QE of 6.4% at 776 nm laser wavelength [3]. Recently, QE exceeding 15% has been demonstrated at near bandgap photon energies with spin polarization just above 62% [4]. With many GaAs/GaAsP superlattice pair, the tuning of DBR resonance peak wavelength, maintaining both high spin polarization and QE is challenging. The resonance peak might not match the emission threshold of typically used 780 nm. Non-uniform doping density within the top 5 nm could notably affect QE and spin polarization. Elevated-temperature heat treatment may induce inter-layer material diffusion. Additionally, the number of DBR pairs needs to be optimized to achieve a high QE peak near the photoemission threshold.

OPTIMIZE PRE-CLEANING AND HEAT TREATMENT

GaAs/GaAsP-based superlattice photocathodes grown using Molecular Beam Epitaxy (MBE) are usually terminated with an Arsenic capping layer to prevent contamination at the surface. The Arsenic capping layer can be easily removed in an ultra-high vacuum (UHV) system with a heat cleaning temperature of over 450°C. And, these do not require wet cleaning since it is protected with As capping layer. The superlattice DBR wafers used in this study were fabricated at Old Dominion University, using the Metal-Organic Chemical Vapour Deposition (MOCVD) system [5]. In a MOCVD system, it is rather challenging to incorporate an Arsenic capping layer. As a result, GaAs when exposed to air during handling and installation can create oxide layer, in general, both Ga and As oxides are created. Heat treatment of around 580°C in UHV usually completely gets rid of all the oxides from the surface. However, heat treatment at around 580°C seems to cause inter-layer material diffusion as we observed in Transmission Electron Microscopy (TEM).

TEM, along with energy dispersive X-ray spectroscopy (EDS) imaging, was performed at the Center for Functional Nanomaterials (CFN) at Brookhaven National Laboratory. TEM analysis was conducted using a FEI Talos F200X TEM/STEM operating at 200 keV, with EDS data collected by four in-column integrated SSD Super-X detectors. Figure 1 shows the TEM image and EDS map of cross-section of the superlattice section of the pristine sample, and the same sample after two cycles of 580°C heat treatment. All of the tested 580°C heat-treated samples show the effects of inter-layer material diffusion.

We wanted to verify if high-temperature heat treatment such as 580°C could cause any reduction in the doping density of the surface layer. The top 5 nm of GaAs/GaAsP superlattice layer is highly ($\sim 10^{19}/cm^3$) p-doped either us-

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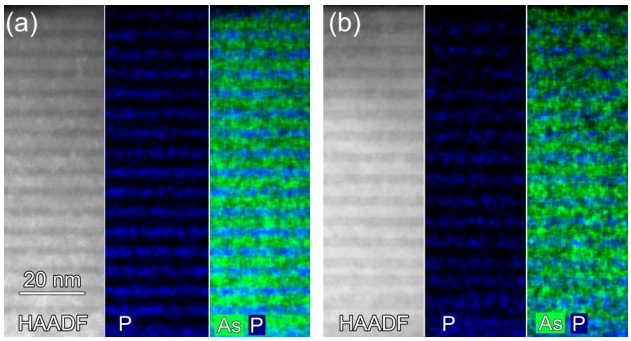

Figure 1: Cross-sectional transmission electron microscopy image and energy dispersive X-ray spectroscopy images of the superlattice section ($GaAs/GaAs_{0.65}P_{0.35}$) of the sample showing the P (center), and As & P peak (right). Image (a) shows a pristine sample and image (b) is for the same sample after it went through two cycles of 580°C heat treatment.

ing Zn or C as the dopant. TEM is not very suitable for GaAs/GaAsP doping analysis since the density of GaAs is $4.5 \times 10^{22}/cm^3$ and a high doping level is only incorporated in the top 5 nm. The sample under discussion in this paper is doped with Carbon in the first 5 nm, and the rest of GaAs/GaAsP layers are doped with Zinc. To study doping density in the surface layer, we have utilized Secondary Ion Mass Spectroscopy (SIMS). Figure 2 shows carbon count per 10k total ion for both pristine sample, and sample from the same wafer after 580°C heat treatment. To avoid background carbon count we have utilized a GaAs sample with no carbon doping as our sample for background correction. Figure 2 clearly shows that high-temperature treatment of around 580°C has adverse effects on the surface layer doping density.

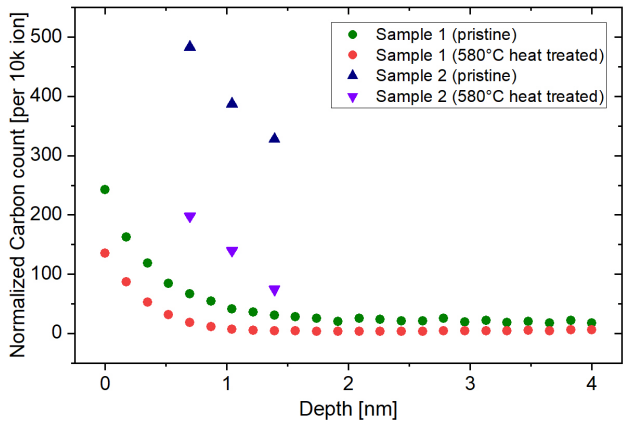

Figure 2: SIMS cross-sectional profile for pristine SL-DBR sample, and sample from the same wafer after it went through two heat cleaning cycle at 580°C. Both for sample 1 and 2, we observed reduction of carbon count in the surface layer.

To reduce the heat cleaning temperature, we have incorporated a wet cleaning method before the sample installation into the vacuum system. We immersed the MOCVD-grown GaAs samples in a 36% purified hydrochloric acid solution for 45 seconds, dipped into deionized water, and followed by blowing them with high-purity dry N_2 for a few seconds, then promptly installing them into the cathode puck (with Indium foil underneath for ohmic contact) and loaded into the chamber through the load-lock manipulator that was baked at 200°C for 72 hours. After the successful bake of the load-lock manipulator section, cathode puck was transferred into the preparation chamber. The base pressure of the preparation chamber was $\sim 1 \times 10^{-11}$ Torr. Figure 3 shows a layout of the Mott polarimeter including a unique load-lock system for easy transfer of cathodes, and an optics setup for circularly polarized light generation. A superk EXTREME white light source along with a monochromator alternative from NKT photonics were used to generate a single wavelength laser with a tunability from 400 nm to 820 nm. Circularly polarized laser was obtained by using linear film polarizer, quarter-wave plate and polarizing beamsplitting cubes, all mounted at the top of the polarimeter and kept inside an enclosure.

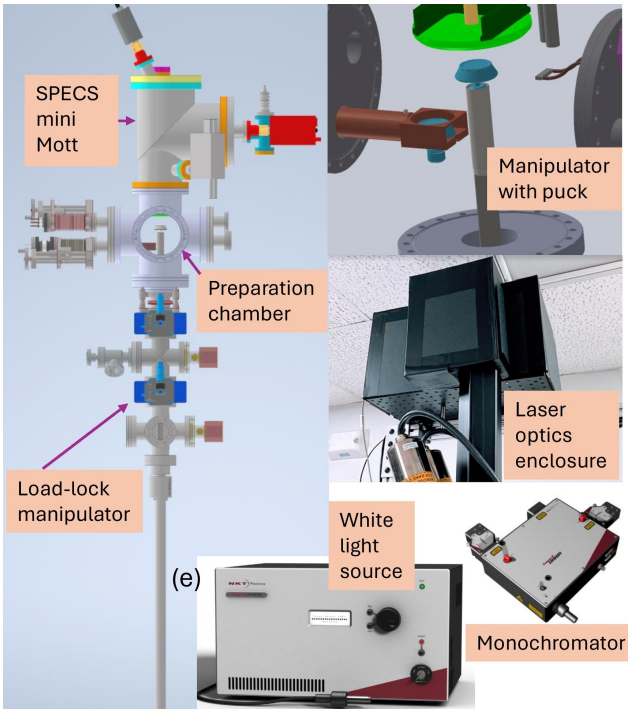

Figure 3: Layout of the Mott polarimeter system, along with load-lock manipulator, cathode activation chamber, and laser optics setup.

The sample was activated at room temperature in the preparation chamber of the Mott polarimeter to form a negative electron affinity (NEA) surface using the standard yo-yo activation procedure with Cs and O_2. The QE of the samples were scanned with a laser with a wavelength ranging from 720 nm to 800 nm. Figure 4 shows the spectral response and spin polarization of a superlattice DBR photocathode. At the center of the wafer, the peak QE wavelength position is close to the intended design value of approximately 780-785 nm. However, peak QE wavelength varies as we move

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from the center towards the edges of the wafer. Our study revealed a shift in peak QE wavelength from 770 nm to 790 nm across a 2-inch sample, indicating non-uniformity in the DBR layer across the sample, possibly due to nonuniform heating during the growth process in the MOCVD system. We are in the process of optimizing the growth recipe to achieve a uniform peak QE position across the wafer.

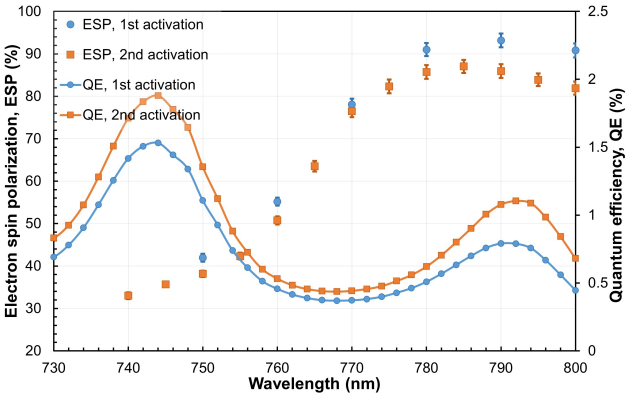

Figure 4: The QE and electron-spin polarization for the GaAs/GaAsP superlattice DBR photocathode as a function of the wavelength, measured at nearly identical location.

In our current study, we have used a reduced heat treatment temperature of 450°C, which is sufficient enough to remove most of the Arsenic oxides from the surface. Though high-temperature heat treatment of around 580°C is able to achieve a contamination-free surface and shows high QE [6], our motivation was to minimize the dopant diffusion at the surface layer so that high bunch charge could be extracted from the cathode in High Voltage Direct Current (HVDC) gun. We found that in terms of achieved polarization from the SL-DBR cathode, there is no difference between 450°C and 580°C heat treatment.

OPTIMIZE SURFACE DOPING AND DBR PAIRS

The top 5 nm of the GaAs/GaAsP superlattice layer are usually terminated with highly p-doped material (i.e., Zinc or Carbon) so that it helps lower the work function, as well as prevent recombination of electrons and holes, making a net increase of emitted electrons from the cathode. Carbon as a dopant has a relatively lower diffusion rate, and hence it was a choice of dopant in our case for the surface layer.

To optimize the surface doping concentration, we tested four DBR superlattice GaAs samples with surface doping levels ranging from 1×10^{19} to 2×10^{20} $/cm^3$. The peak polarization starts to decline beyond $5 \times 10^{19}/cm^3$ due to the scattering of doping atoms with polarized electrons, leading to polarization degradation. Lower doping levels typically yield higher spin polarization, whereas higher surface doping helps suppress the surface charge effect while extracting electron beam in a gun. Considering the figure of merit (P^2QE) of the polarized source, where P represents polarization, achieving high polarization is the most crucial factor. Therefore, based on this criterion, we determine to use the sample with the highest figure of Merit, which has the optimal surface doping level of $5 \times 10^{19}/cm^3$.

A sample with an optimal surface doping of $5 \times 10^{19}/cm^3$ underwent pre-cleaning with HCL and a reduced heat treatment temperature of around 450°C in UHV. Subsequently, it was activated and tested in HVDC electron gun [7]. The HVDC gun was operated at 300 kV, and the test of the SL-DBR cathode in the HVDC gun shows that a lower heat cleaning temperature of 450°C (compared with traditional 580°C heat treatment) helps to suppress the surface charge effect. Details of this study will be discussed elsewhere.

To optimize the number of DBR pairs we have utilized samples with varied DBR pairs, ranging from 12, 16, and 20 pairs. The DBR pair is composed of alternate layer of $GaAs_{0.65}P_{0.35}$ and $In_{0.30}Al_{0.70}P$. The DBR pairs were Zn doped with a doping density of $5 \times 10^{18}/cm^3$. The very surface carbon doping of all these samples were close to $5 \times 10^{19}/cm^3$. The main purpose of the DBR layer is to increase absorption of photon in GaAs at a desired wavelength. However, having too many DBR layers could increase the cavity Q factor, causing a smaller bandwidth and a drop in QE. Figure 5 shows a comparison of the figure of merit (P^2QE) for different DBR pair numbers with respect to wavelength. A higher figure of merit was achieved for the sample with 16 DBR pairs.

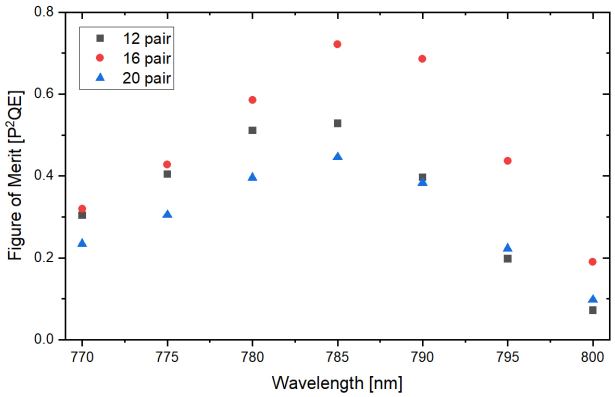

Figure 5: Figure of merit (P^2QE) for superlattice DBR sample with a varied number of DBR pairs.

SUMMARY

In summary, we have optimized the pre-cleaning and heat treatment of MOCVD-grown superlattice DBR GaAs/GaAsP cathodes that do not have any capping layer. Wet etching was performed with HCL, and the heat treatment temperature was reduced to around 450°C to minimize high-temperature-induced diffusion of dopant material. Testing of the SL-DBR was performed in a mini Mott polarimeter to identify the optimal doping density in the surface layer, as well as the number of DBR pairs for a high figure of merit at near bandgap photon energies.

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