ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPA131

HIGH VOLTAGE DC GUN USING DISTRIBUTED BRAGG REFLECTOR SUPER LATTICE GaAs PHOTOCATHODE FOR EIC POLARIZED ELECTRON SOURCES*

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Abstract

The polarized electron source is a critical component of the electron-ion collider and requires a polarized electron gun with higher voltage and higher bunch charge than existing sources. At Brookhaven National Laboratory, the inverted HVDC photoemission gun has been successfully conditioned up to 350 kV. Our study presents the performance of a bulk GaAs photocathode using a circularly polarized laser at 780 nm wavelength, generating an average current of 70 μA and up to 16 nC bunch charge with a long lifetime. We also discuss the performance of a Distributed Bragg Reflector(DBR) GaAs/GaAsP Super Lattice(SL) photocathode in the DC gun, and possible reasons for the observed peak QE wavelength shift are analyzed. In addition, the impact of DBR layer and laser on the lifetime has been discussed. Further investigations are required to assess the DBR GaAs sample and enhance the performance of the polarized electron gun.

INTRODUCTION

Brookhaven National Laboratory has successfully designed and commissioned a high voltage direct current (HVDC) polarized electron gun utilizing bulk GaAs material with a 785 nm circularly polarized laser. The gun was conditioned up to 350 kV without any observed field emission, and it was operated consistently at 300 kV as reported in Ref. [1]. The maximum charge generated from the bulk GaAs photocathode was measured to be 16 nC. Furthermore, the lifetime of the gun is orders of magnitude longer than the requirement for the polarized electron source of the Electron-Ion Collider (EIC). The gun test facility is situated at the physics department of StonyBrook University. The gun and its test beamline is shown in Fig. 1. Five solenoids maintain the beam envelop until the beam is delivered to the beam dump. A 16° bending dipole is placed after the 2nd solenoid. The dipole magnet prevents the charged particles from downstream from tracing back to the gun and also can be used for energy spectrum. The circularly polarized laser is delivered to the cathode, normal to the cathode surface, through the dipole chamber.

One integrated current transformer (ICT) and Faraday cup are used to measure bunch charge. Four yttrium aluminum garnet(YAG) beam profile viewers are installed in the beamline to measure the beam transverse profile from the gun to the beam dump. Two beam position monitors (BPM) are used to monitor beam positions before and after the dipole during the operation.

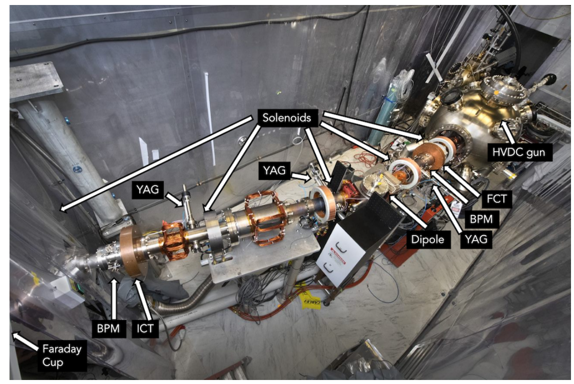

Figure 1: Layout of polarized gun and test beamline.

The Faraday cup with radiation shielding can take up to 100 μA average current with vaccum stablized at 10^{-9} torr. Higher current will cause the beamline dynamics vacuum pressure goes up and impact the cathode lifetime measurement. Considering the EIC electron source average current requirement is 56 nA. Therefore, most of our tests'average current is lower than 75 μA.

DBR STRAINED SUPERLATTICE GAAS

The typical strained superlattice GaAs exhibits a quantum efficiency (QE) of less than 1% with polarization around 90%. Moreover, this photocathode is highly sensitive to residual gas pressure, which presents a challenge in its use for a wide range of applications due to its low QE and short lifetime. To address these limitations, a distributed Bragg reflector (DBR) layer was added to the GaAs photocathode, resulting in a Fabry-Perot resonance in between the surface-vacuum interface and DBR layer that significantly enhances the QE. The first report of a GaAs photocathode with a DBR layer was in 1993, and subsequently, the QE record of up to 6.4% was achieved by JLab/SVT collaboration in 2016 [2]. Recently, Old Dominion University has been developing the same DBR structure using the MOCVD method, which offers a more efficient way to grow the cathode. In preliminary trials, a decent QE and good polarization have been achieved, as shown in Fig. 2.

The QE is better than the strained superlattice GaAs photocathode. So we tested this sample in the HVDC gun.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy
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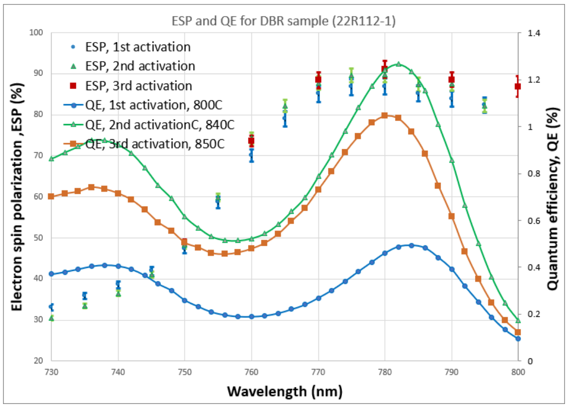

Figure 2: The QE and polarization measured at Mott polarimeter.

GUN TEST RESULTS USING DBR GAAS PHOTOCATHODE

We employ a HCl rinsing process before installing the DBR strained superlattice GaAs into the activating chamber due to the absence of an As cap. The cathodes are then subjected to heat treatment up to a temperature range of 560 – 580°C for 1 hour at a ramping rate of 3°C/min, following the same activation procedure used for bulk GaAs. After the cathode has cooled to room temperature, successive deposition of Cs and O_2 can result in a peak quantum efficiency (QE) of about 1.2% at a wavelength of 780 nm, which is comparable to the Mott measurement.

Furthermore, the gun laser has been upgraded to be wavelength-tunable, now capable of covering the range of 760-800 nm. After activating the cathode, the gun voltage can be safely increased to 350 kV without any observed field emission. Despite the presence of some defects on the cathode surface, there is no impact on the high voltage performance. The maximum bunch charge extracted from the cathode is 6.5 nC with a 1.6 ns full-width at half-maximum (FWHM) pulse length. The charge limit is mainly caused by the surface charge limit, rather than the space charge limit, which is at 12 nC for an identical laser pulse. However, it is possible that the temperature of 560 – 580°C used during heat clean may be too high, leading to the diffusion of the heavily carbon-doped surface layer. Another potential cause for the reduced charge limit is that the doping concentration may not be sufficiently high, and the cathode growth process is still being optimized. The lifetime of DBR GaAs cathode measurements shows In 6 hours tests, DBR GaAs extracted 20 times more charges than EIC needs for one week. The QE decay is minimal.

One of the most important observations is that the peak QE has shifted unexpectedly to 770 nm in the 300 kV gun. Figure 3 shows the QE as a function of wavelength around the peak with parabolic fitting. The wavelength at which the peak QE occurs is similar between the Mott polarimeter and cathode activation chamber. However, the QE absolute values quoted in the Fig. 3 measured in the activation chamber and gun should be considered relative due to the lack of proper calibration of the laser power. When we normalized the peak QE value, the parabola quadratic term is comparable, that indicates the Q factor of the Frabery-Perot resonance is not impacted. Further studies are planned. But the peak QE shift in the peak wavelength is more interesting to be investigated.

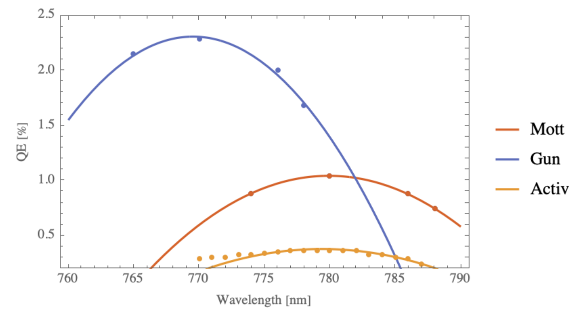

Figure 3: The QE wavelength scan with parabola fitting, in the Mott polarimeter, Gun and activation chamber.

DISCUSSION

Possible Reasons for Resonance Peak Shift

The difference between the Mott polarimeter and gun test is solely the high voltage applied to the cathode. Therefore, we investigated the potential impact of the field gradient on the resonance wavelength shift. Nonlinear optical properties of semiconductors suggest that the refractive index of a material can be altered by the strength of an applied electric field. This effect is only possible in non-centrosymmetric materials. GaAs is a typical a compound with a zinc blend crystal structure, which is a non-centrosymmetric material. Two possible mechanisms for the observed phenomenon are proposed: i) the Pockels effect, and ii) the Kerr effect.

In order to study these two effects, we first established a interband transition model using the transfer matrix model described in Ref. [2]. The DBR superlattice GaAs cathode has the layer material of GaAs, GaAsPx, and AlAsP. The phospher rate and layers thickness was optimized to achieve required strain and resonance without external field. Each material has its permittivity as the function of photon energy as $\epsilon = \epsilon_1 + i\epsilon_2$. The refractive index $n = \sqrt{\epsilon}$ is a complex function as well. The real part refractive index indicates the phase velocity, while the imaginary part κ is absorption coefficient as shown

$$I(x, \lambda) = I_0 e^{\frac{-4\pi\kappa x}{\lambda}} . \quad (1)$$

The transfer matrix with in the layer can be written as:

$$f(k, d) = \begin{pmatrix} e^{-ikd} & 0 \\ 0 & e^{-ikd} \end{pmatrix} , \quad (2)$$

where the $k = n\frac{2\pi}{\lambda}$ is the wavenumber in the material. The transfer matrix between two layers can be written as:

$$j(k_a, k_b) = \frac{1}{2} \begin{pmatrix} 1 + \frac{k_a}{k_b} & 1 - \frac{k_a}{k_b} \\ 1 - \frac{k_a}{k_b} & 1 + \frac{k_a}{k_b} \end{pmatrix} . \quad (3)$$

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The $j(k_a, k_b)$ means the light incident from material with wavenumber k_a into k_b. In the DBR SL GaAs, there are more than 30 layers involving. The overall transfer matrix is

$$\begin{pmatrix} T_{11} & T_{22} \\ T_{21} & T_{22} \end{pmatrix} = f(k_n, d_n)j(k_{n-1}, k_n)f(k_{n-1}, d_{n-1})\dots \\ j(k_1, k_2)f(k_1, d_1)j(k_0, k_1) , \quad (4)$$

where k_0 is permittivity in vacuum. From Eq. (4), we can obtain the transmission (T) and reflection(R). The QE is proportional to the absorption(A) which is $A = 1 - T - R$. The basic QE of nonDBR can be fitted by experimental data. Without the external field, we can get the QE as the function of wavelength as shown in

The resonance wavelength is highly impacted by the wave number which can be changed by the external field via complex fraction index.

There is another factor is resonance wavelength change by changing the layer thickness. The GaAs wafer is installed in the cathode plug which pressed to the gun plug holder with 30 pounds force which may deliver to the cathode. The thickness can be reduced via crystals Young's modulus. To reduce wavelength by 10 nm, the refraction has to be reduced by 0.04 or the thickness changes by 12 nm for overall 500 µm samples. The QE spectrum response changes are shown in Fig. 4.

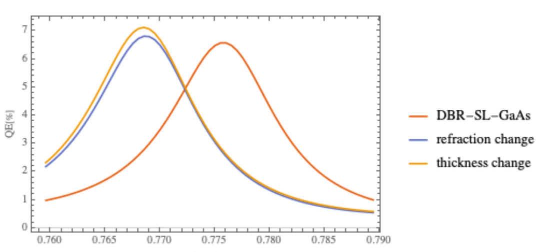

Figure 4: The peak QE wavelength change caused by the refraction and thickness change.

The Pockels electro-optic effect caused the refractive index change can be written by:

$$\Delta n L = \frac{n^3 r_{41} V L}{2d} . \quad (5)$$

Here $r_{41} = 1.36\, pm/V$ and n is refraction index , V is the field gradient [3]. For 4 MV/m gradient, the pockels effect can change the refraction index by 0.00001 at around 780 nm.

The Kerr effect is an non-linear electro-optic effect which proporional to the square of the electric field [4]. It can be evaluated by:

$$\frac{2\pi}{\lambda} L \Delta n = 2\pi \chi L E^2 , \quad (6)$$

where χ is nonlinear coefficients. For GaAs/AlGaAs, the $\chi = 750\, pm/V$. At 780 nm, the Kerr effect induced refraction change is about 0.00005.

Based on our analysis of the Pockels effect, Kerr effect, and Young's modulus, we estimate that the total wavelength change caused by these factors is approximately 1 nm. This value is around 10% of the observed wavelength change. In order to gain a better understanding of the behavior of the DBR GaAs sample, we are currently in the process of developing a device to measure its response under varying conditions of voltage and pressure. Further experiments will be necessary to fully characterize the impact of these factors on the resonance wavelength of the sample.

Lifetime Impacts by the DBR

The cathode QE is determined by the photon energy hv, surface electron affinity (Ea). When $h\nu \simeq Eg + Ea$, any small variation in Ea could affect the QE dramatically.We have observed that the QE slope of the DBR SL GaAs cathode and regular GaAs cathode is significantly different at wavelengths longer than the peak. As shown in Fig. 5, the slope of the DBR SL cathode curve is approximately 2 %/5nm, while the slope of the SL GaAs cathode is approximately 0.2 %/5nm. This indicates that the SL-GaAs cathode QE above 780 nm is ten times less sensitive than the DBR SL GaAs cathode at the same range.

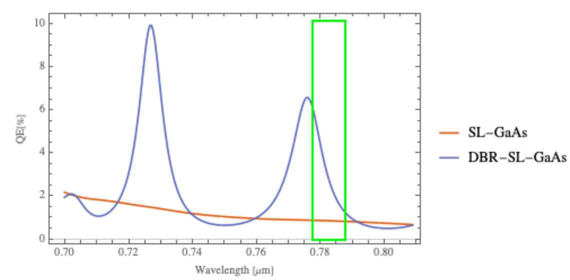

Figure 5: The QE as the function of wavelength for the DBR SL GaAs. The peak QE wavelength is at 778 nm which matches to our experimental results. The non DBR photocathode QE is using experimental data fitted.

To improve the lifetime and preserve the polarization, we propose to operate the DBR cathode at wavelengths shorter than the peak QE wavelength, where the slope is reversed, indicating better lifetime. We aim to shift the DBR cathode resonance wavelength towards the longer side, which may reduce the final QE, but will be beneficial in terms of lifetime and polarization preservation. Therefore, pursuing a high QE by shifting the peak wavelength to the short side is not a recommended approach.

CONCLUSION

We have established the HVDC gun which can operate at 300 kV with 7 nC polarized electron beam, using bulk GaAs, stably. In our preliminary test, we tested DBR SL GaAs in the gun, generated 6.5 nC bunch charge and showed good lifetime. We observed the peak QE wavelength shifted to the short wavelength direction by 10 nm. The linear and nonlinear electro-optic of GaAs effect and pressure effect have been discussed to explain the result. We also proposed how to select the appropriate wavelength in the DBR GaAs cathode to avoid lifetime degrade.

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