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Recent Polarized Photocathode R&D at SLAC[*]

D.-A. Luh, A. Brachmann, J. E. Clendenin, T. Desikan, E. L. Garwin, S. Harvey, R. E. Kirby, T. Maruyama, and C. Y. Prescott,
Stanford Linear Accelerator Center, Stanford University, Menlo Park, CA 94025

R. Prepost
Department of Physics, University of Wisconsin, Madison, WI 53706

Abstract

The SLAC high-gradient-doped MOCVD-grown GaAs cathode presently in use consists of a strained GaAs low-doped layer (with a small admixture of P) capped by a few nanometers of highly Zn-doped GaAs, which is heat-cleaned at relatively high temperature and then activated by Cs/NF_3 co-deposition. The high-gradient-doped structure solves the problem of the surface charge limit that the previously-used SLAC cathodes had, and this preparation procedure has produced satisfactory results. However, the preparation procedure has a few weaknesses that prevent cathodes from achieving the ultimate desired performance. The peak polarization is limited to 80% due to strain relaxation in the relatively thick strained layers. Also dopant loss causes the surface charge limit effect to reappear after multiple high-temperature heat-cleanings. In this paper, we will discuss recent progress made at SLAC that addresses these limitations, including using the MBE growth technique with Be doping and using the superlattice structure. In addition, to reduce the heat-cleaning temperature, an atomic hydrogen cleaning technique is explored.

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[a]*Stanford Linear Accelerator Center, Menlo Park, CA 94025*
[b]*Department of Physics, University of Wisconsin, Madison, WI 53706*

Abstract. The SLAC high-gradient-doped MOCVD-grown GaAs cathode presently in use consists of a strained GaAs low-doped layer (with a small admixture of P) capped by a few nanometers of highly Zn-doped GaAs, which is heat-cleaned at relatively high temperature and then activated by Cs/NF_3 co-deposition. The high-gradient-doped structure solves the problem of the surface charge limit that the previously-used SLAC cathodes had, and this preparation procedure has produced satisfactory results. However, the preparation procedure has a few weaknesses that prevent cathodes from achieving the ultimate desired performance. The peak polarization is limited to 80% due to strain relaxation in the relatively thick strained layers. Also dopant loss causes the surface charge limit effect to reappear after multiple high-temperature heat-cleanings. In this paper, we will discuss recent progress made at SLAC that addresses these limitations, including using the MBE growth technique with Be doping and using the superlattice structure. In addition, to reduce the heat-cleaning temperature, an atomic hydrogen cleaning technique is explored.

CURRENT PROCEDURES

The cathode used in the current accelerator operation at SLAC is a high-gradient-doped strained GaAs/GaAsP [1]. The MOCVD-grown cathode consists of a strained GaAs low-doped layer (with a small admixture of P) capped by a few nanometers of highly Zn-doped GaAs. When the 2-inch cathode wafer is received, it is anodized at 2.5V to form a 3-nm oxide protecting layer, and then waxed on glass and cut to the required circular shape. When the cathode is ready for installation, the glass is removed, and the cathode is degreased in boiling trichloroethane. After degreasing, the surface oxide of the cathode is stripped by ammonium hydroxide, and the cathode is immediately transferred into a loadlock. The cathode is heat-cleaned at 600°C for one hour and activated by Cs/NF_3 co-deposition. In our standard procedure, heat cleaning and activation are done twice before the cathode is transferred into the polarized electron gun.

WEAKNESSES

Although our standard procedures for cathode preparation have yielded satisfactory results, it has a few weaknesses that have prevented cathodes achieving the ultimate desired performance.

MOCVD: The base pressure in MOCVD growth chambers is usually in high-vacuum range. Compared with ultra-high-vacuum techniques, the growth environment of MOCVD may not be as clean. Furthermore, because chemical reactions are needed on wafer surfaces during growth, MOCVD requires higher growth temperature, and its growth mechanism is complicated. Due to the nature of the MOCVD process, it may be difficult to grow thin films of the highest quality.

Zn dopant: The diffusion coefficient of Zn in GaAs is high at the heat-cleaning temperature in our preparation procedure (600°C). Because of the high diffusion coefficient, the heat-cleaning capability of Zn-doped cathodes is very limited. In high-gradient-doped cathodes, the highly doped surface layer is responsible for removing the surface-charge-limit effect in high photocurrent operations [1], and dopant loss is very undesirable.

The SIMS (Secondary Ion Mass Spectroscopy) analysis shown in Fig. 1 confirms the Zn-dopant loss after cathodes receive heat-cleaning treatments. Before the cathode is heat-cleaned, the Zn-dopant concentration is $5\times10^{19}cm^{-3}$ as specified [1]. After 5 hours of heat-cleaning at 600°C, the Zn-doping level at surface drops significantly. A test on a Zn-doped high-gradient-doped cathode indicates that the cathode starts to show the surface-charge-limit effect after three hours of heat-cleaning at 600°C.

Strain relaxation in single strained layer: The high-gradient-doped cathode has a 90nm thick strained GaAsP as its active layer. The strain in the active layer is responsible for the polarization of photoelectrons, and strain relaxation in the active layer will lower the polarization.

A strained layer starts relaxing when its thickness exceeds the critical thickness. It relaxes completely when its thickness exceeds the practical thickness. It is partially relaxed when its thickness is between the critical thickness and the practical thickness. In the case of GaAs or GaAsP, the critical thickness is about 10nm, and the practical thickness is about 100nm. Table 1 shows the comparison of the performance between two cathodes. Both cathodes are high-gradient-doped strained GaAs/GaAsP. The only difference between the two cathodes is the thickness of their active layers. The polarization of the cathode MO5-6007 is considerably lower due to the strain relaxation in its active layer.

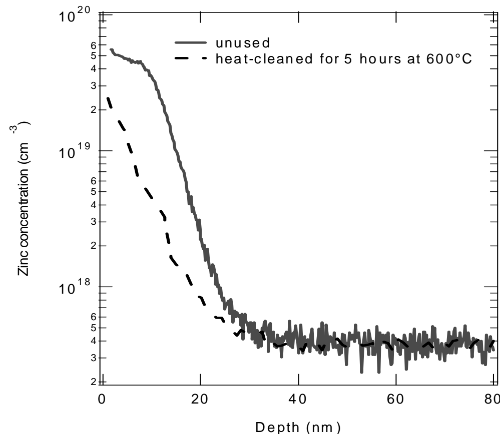

FIGURE 1. SIMS analysis for the cathode before and after heat cleanings.

TABLE 1.

Cathode No.	Active Layer Thickness (nm)	Polarization (%)
MO5-5868	90	82
MO5-6007	170	70

IMPROVEMENTS AND PROGRESS

To address the weaknesses in the standard cathode growth and preparation procedure, a few improvements can be made.

MBE and Be/C doping: Our cathode growth technique has been switched from MOCVD with Zn doping to MBE with Be doping. The ultra-high vacuum of MBE growth ensures a clean growth environment. MBE growth usually requires a lower growth temperature and has a simpler growth mechanism. All these advantages make the growth of high-quality layers easier. Be and C have much lower diffusion coefficients than Zn, and Be-doped and C-doped cathodes will have better heat-cleaning capability.

Fig. 2 shows the performance of the two cathodes from wafers SVT-3982 (MBE-grown Be-doped) and MO5-5868 (MOCVD-grown Zn-doped), tested in Cathode Test Laboratory (CTL) at SLAC. Both cathodes are high-gradient-doped strained GaAsP with the same structure. The result shows that the performance of MBE-grown SVT-3982 is better than MOCVD-grown SVT-5868. The heat-cleaning performance of the Be-doped SVT-3982 is yet to be tested.

As-capped cathodes: MBE allows As capping at the end of the wafer growth. A thin As cap layer is sufficient to protect cathode surface from exposure to air, and can be removed by heat-cleaning at lower temperature.

Atomic hydrogen cleaning: Another method to lower the heat-cleaning temperature is to use atomic hydrogen cleaning. The idea is to use atomic hydrogen generated by a RF dissociator to react with and remove oxide and carbon contamination from cathode surface at a lower temperature. Fig. 3 shows the preliminary results from the atomic hydrogen cleaning system in CTL [2]. The reference cathode is GaAs, stripped of its oxide layer by NH_4OH, heat-cleaned, and activated by Cs/NF_3 co-deposition. The result shows that the QE increases with increasing heat-cleaning temperature, which indicates that the thin oxide layer on the cathode surface from the short air exposure is gradually removed as the temperature increases. The GaAs test cathode is treated as indicated in the figure and then activated by Cs/NF_3 co-deposition. Because the test cathode is not stripped by NH_4OH, the cathode surface starts with a thick native oxide layer. As the data indicates, repetitive

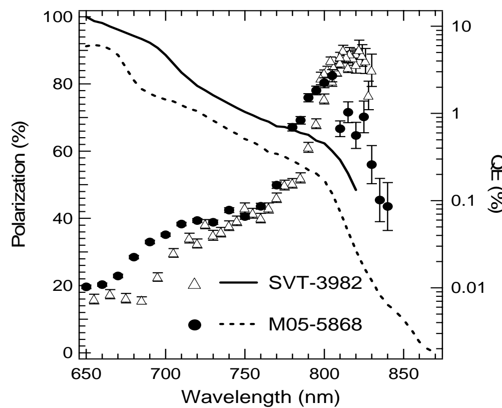

FIGURE 2. The performance comparison between MBE-grown Be-doped (SVT-3982) and MOCVD-grown Zn-doped (MO5-5868) cathodes.

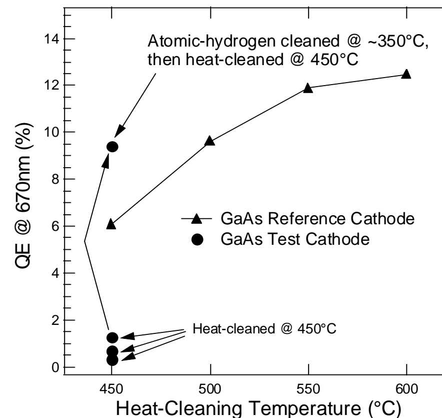

FIGURE 3. Preliminary results from atomic-hydrogen cleaning system.

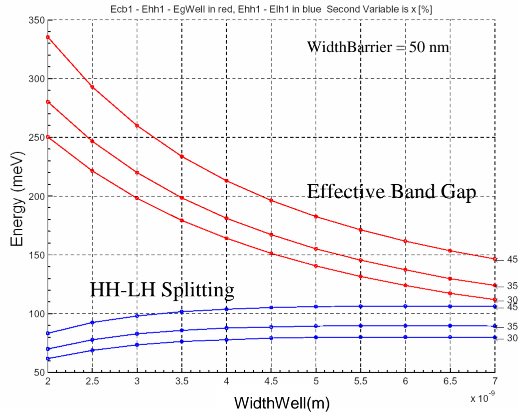

FIGURE 4. Typical results from band structure calculation.

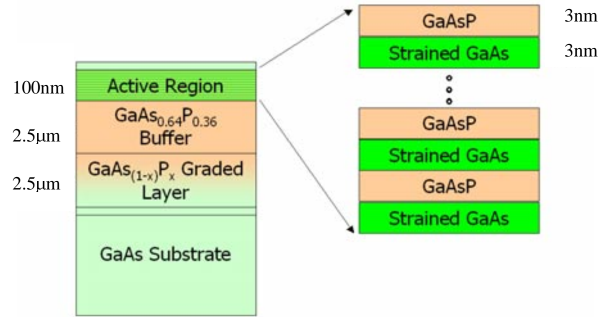

FIGURE 5. The structure of high-gradient-doped superlattice cathodes (SVT-3682 and SVT-3984).

heat-cleanings at 450°C cannot remove the oxide layer effectively, and thus the QE is very low. After one hour of atomic hydrogen cleaning, the QE is greatly improved and is similar to that from the reference cathode heat-cleaned at 500°C. Later studies have demonstrated that it is possible to produce cathode with a QE higher than 14% from unstripped GaAs cathode by atomic-hydrogen cleaning (not shown in the figure). However, these studies also indicate that excessive atomic hydrogen cleaning yields GaAs cathode surfaces with low QE. Work continues to optimize the conditions for atomic-hydrogen cleaning.

Superlattice photocathodes: The superlattice structure is employed to preserve strain in the active layer of photocathodes. The idea is to grow strained layers sandwiched between unstrained layers, where the thickness of each strained layer is less than the critical thickness.

1. A band structure calculation is performed to determine the proper structure parameters to grow superlattice cathodes. The transfer matrix method [3] is used for the calculation. Fig. 4 shows typical results of effective band gap and heavy-hole-light-hole (HH-LH) splitting from the calculation. In this figure, the barrier width is fixed at 50 nm, while the well width and the phosphorus fraction are allowed to change. Because the cathode QE is related to the band gap, and the polarization is related to HH-LH splitting, the result from calculation can be used to predict roughly how the cathode QE and the polarization will change when the structure parameters are varied.

2. Photoluminescence measurements are performed on cathode wafers to check the cathode band structure. This provides a way to check the accuracy of the band structure calculation. Furthermore, it also checks the uniformity of cathode wafers if the photoluminescence measurements are performed on entire wafers.

3. X-ray diffraction is done to characterize the cathode structure when cathode wafers are received from vendors. By studying x-ray diffraction patterns, structure parameters can be determined, including layer thickness, composition, and strain.

Fig. 5 shows the structure of the first superlattice cathode we studied. The structure parameters of the cathode are similar to the ones reported in Ref. [4]. In this superlattice cathode, strained GaAs layers are sandwiched by GaAsP layers. Both the well and barrier widths are 3nm. The phosphorus fraction in the GaAsP is 0.36. A 5nm

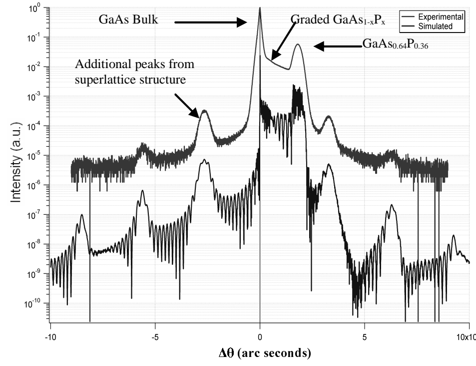

FIGURE 6. Results of (004) scan on a superlattice cathode from experiments (top) and simulations (bottom).

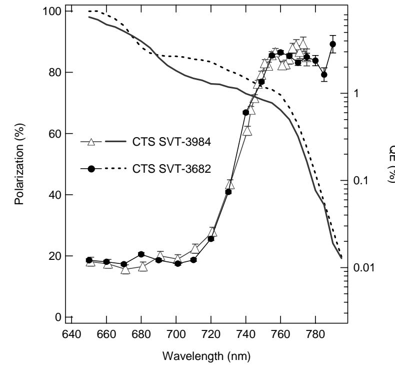

FIGURE 7. Performance of high-gradient-doped superlattice cathodes SVT-3682 and SVT-3984.

highly-doped GaAs layer is grown on the surface of the superlattice cathode to address the surface-charge-limit problem.

Fig. 6 shows the result from a (004) scan in an x-ray diffraction measurement. The experimental results from show all the familiar features. The Bragg peaks from GaAs bulk, graded GaAsP, and GaAsP are clearly identified. Additional peaks from the superlattice structure can also be seen. The simulation results show that the barrier width and the well width are about 32Å with the phosphorus fraction about 0.36. These numbers are very close to the structure design.

The performance of two superlattice cathodes is shown in Fig. 7. Both cathodes show good QE, and their peak polarizations are over 85%. One cathode from the wafer SVT-3984 has been tested in Gun Test Laboratory at SLAC, and there is no surface charge limit observed with available laser energy.

CONCLUSIONS

Although the standard cathode growth and preparation procedure at SLAC has yielded satisfactory results, there is still room for improvement. Dopant loss during high-temperature heat-cleaning and strain relaxation in single strained layer have prevented cathodes from achieving ultimate performance. MBE-grown Be-doped cathodes are expected to be of higher quality and higher heat-cleaning capability than MOCVD-grown Zn-doped cathodes. To reduce the heat-cleaning temperature, an atomic hydrogen cleaning system has been set up. Preliminary tests show promising results although the operational conditions are yet to be optimized. The superlattice structure is employed to preserve strain. The first superlattice cathodes have shown both good QE and good polarization.

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