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Transport Mechanisms in Polarized Semiconductor Photocathodes

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Abstract. We investigated the effect of an accelerating field on the spin polarization of photo-generated electrons in a 100nm thick GaAs based photocathode active region. By decreasing the transport time of the electrons and the number of scattering events that cause depolarization, we expected to increase the polarization as was indicated by Monte Carlo simulations of the scattering and transport time statistics of the electrons.

A tungsten (W) grid was deposited on the cathode surface to provide a uniform voltage distribution across the cathode surface. The metal grid formed a Schottky contact with the semiconductor surface. The bias voltage was primarily dropped at the metal semiconductor interface region, which is the cathode active region. For positive surface bias, the accelerating voltage not only increased the polarization, but it also enhanced the quantum efficiency of the photocathode. Preliminary results verify the bias effect on both quantum efficiency and polarization by a factor of 1.8 and 1% respectively.

Keywords: polarized electron, drift, spin

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INTRODUCTION

The GaAsP/GaAs superlattice (SL) structure has been widely recognized as the most efficient spin polarized electron source with 90% maximum polarization and

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more than 1% quantum efficiency. The main spin depolarization mechanisms in these structures are:

1. Interband absorption smearing due to band-edge fluctuations;
2. Hole scattering between the HH and LH states that causes a broadening of the LH band;
3. Spin precession due to an effective magnetic field generated by the lack of crystal inversion symmetry and spin orbit coupling (DP);
4. Electron-hole scattering (negligible compare to 3);
5. Less polarization selectivity in the band bending region (BBR);
6. Scattering and trapping of electrons in the BBR.

The first two mechanisms are related to the HH-LH splitting for supporting the spin selection rules. A systematic study on the GaAs/GaAsP structure [1] showed that after a certain splitting level, no increase of polarization could be obtained. Mechanisms 5 and 6 are related to the effects of the BBR and will be independently studied in the future. Mechanisms 3 and 4 are material related and they take place during the transport of electrons in the photocathode active region. They are primarily related to the total transport time of the electrons in the active region and the number of scattering effects of the electrons during the transport. In the GaAs/GaAsP SL, the electrons tunnel through high barriers in order to reach the cathode surface. Thus, the electrons are delayed to reach the surface due to the scattering at the high barriers and they interact strongly with the holes because they are confined in the wells. In order to decrease the time of the electrons in the active region and the number of electron scattering events, we introduce an acceleration field for the electrons towards the cathode surface. The field is applied through a Schottky contact at the cathode surface. The accelerating field decreases the transport time of the electrons by a factor of 5-10, thus, significantly decreasing the effect of the Dyakonov-Perel (DP) depolarization mechanism. At the same time, the cathode region is mostly depleted; hence, the electron hole scattering depolarization mechanism does not take place. Finally, when the electrons have a certain energy range between 0.05 and 0.1eV the total number of scattering rates is significantly decreased, as was indicated by Monte Carlo simulations and verified experimentally.

A metal grid was deposited on samples with different structure and doping concentrations at Saxet Interface, Inc. I-V curves and quantum efficiency (QE) measurements were performed at Saxet Interface, Inc. These measurements were repeated at SLAC along with polarization measurements. The results are presented in this paper.

QE AND POLARIZATION AS FUNCTIONS OF THE ELECTRON TRANSPORT MECHANISM

In the case of thin films (<100nm) the QE and polarization can increase by decreasing the transport time of the electrons and decreasing the total number of scattering events (equations 1,2).

$$Y = (1-R)\frac{\tau_1}{\tau_1 + \tau_{em}}\alpha d \tag{1}$$

$$\frac{P_2}{P_1} = \frac{1 + \dfrac{\tau_{em1}}{\tau_{s1}}}{1 + \dfrac{\tau_{em1}}{\tau_{s1}}\left(\dfrac{s_2}{s_1}\dfrac{\tau_{em2}}{\tau_{em1}}\right)} \tag{2}$$

where:
τ_{em}: transport ime of the electron in the active region
τ_1: electron lifetime in the structure
τ_s: electron spin lifetime in the structure
α: optical absorption coefficient
R: reflection coefficient
P: electron polarization upon excitation with circularly polarized light
s: total number of scattering events.

By decreasing the transport time (emission time) of the electrons in the cathode, all depolarization mechanisms are suppressed. Independently of the decrease of the emission time, the decrease of the total number of scattering events increases polarization as is shown in equation 2. Based on the scattering rates in GaAs as a function of energy (Fig. 1), it is possible to minimize the total number of scattering events when electrons have energies in the 0.05-0.1eV region. Electrons can acquire such energies inside the cathode active region during the presence of an accelerating field of ~0.1V/100nm. For such fields, the cathode area can be completely depleted when the doping concentration of the active region is ~10^{17}cm^{-3}.

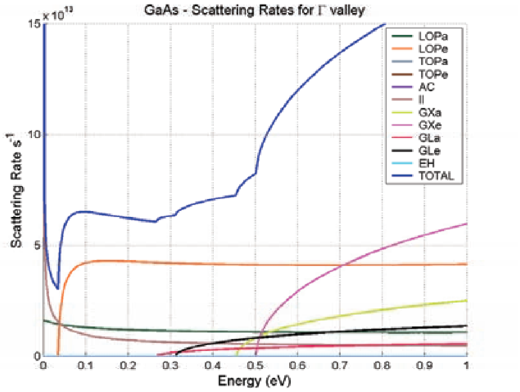

FIGURE 1. Electron scattering rates in GaAs

In the presence of such accelerating field, the electron transport time decreases by an order of magnitude to less than 1ps as it has been estimated by Monte Carlo simulations (Fig. 2) and verified experimentally [2],[3].

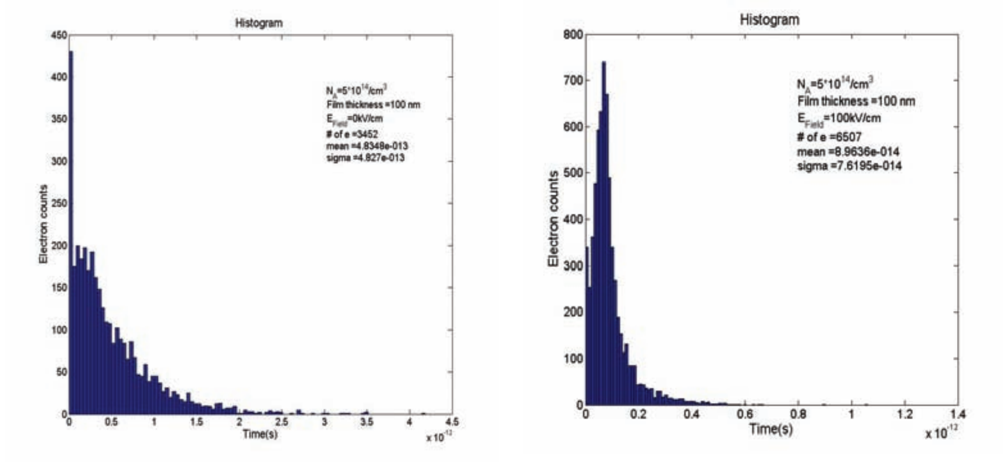

FIGURE 2. Monte Carlo simulations of electron transport inside 100nm GaAs films with diffusion and drift.

The same simulations indicate that the total number of scattering events is decreased significantly due to effect of such fields (Fig. 3).

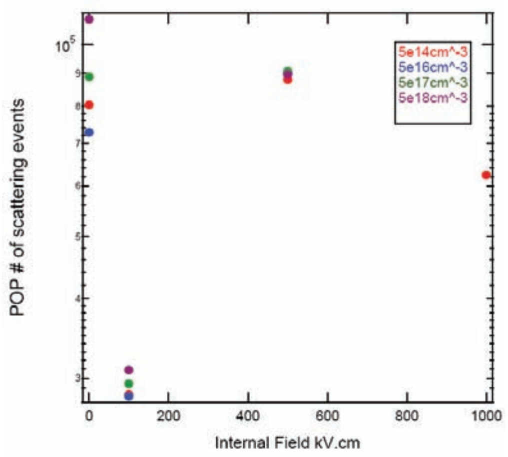

FIGURE 3. Monte Carlo simulations of electron scattering events inside 100nm GaAs films with diffusion and drift.

The decrease of the transport time by an order of magnitude and the reduction of scattering events increases the polarization based on the simple model of equation 2. An increase of 5-10% in polarization is expected by accelerating the electrons in the ~ 0.1eV region.

EXPERIMENTAL RESULTS

Based on Poisson simulations, the spacing between the metal wires of the metal grid should be less than 200 µm in order to preserve uniform potential at the cathode surface. At the same time, the metal lines have to be at least 1 µm thick in order to avoid ohmic losses on the grid. The metal grids need to provide a Schottky rather than an ohmic contact at the cathode surface which is preserved after heat-cleaning of the samples above 500°C. At the same time, W was sputtered at the back surface of the cathode substrate establishing an ohmic contact there. The voltage was applied between the top and bottom surface of the samples through a tantalum ring and electrical feed-throughs. Three different W deposition methods were used in order to achieve the right properties of the metal grid.

1. Photolithography, e-beam evaporation and lift-off of 30nm thick W grids.
2. Use of physical mask, e-beam evaporation and lift-off of 100nm thick Au/10nm thick W lines.
3. Use of physical mask and sputtering of 1µm thick W lines

The samples with thin grid tested are shown in table 1:

Table 1. Sample parameters

Sample #	Active area Thickness	Doping(cm^{-3})	Grid size: metal/no metal (µm)
18A,16A	100 nm	5e16	4/16
19B	100 nm	5e14	4/16

Thick W lines were deposited on the same wafers with a physical mask but the Schottky contacts did not survive the heat-cleaning.

Using samples with metal grids, we observed the bias effect on both the quantum efficiency and polarization (Fig. 4,5).

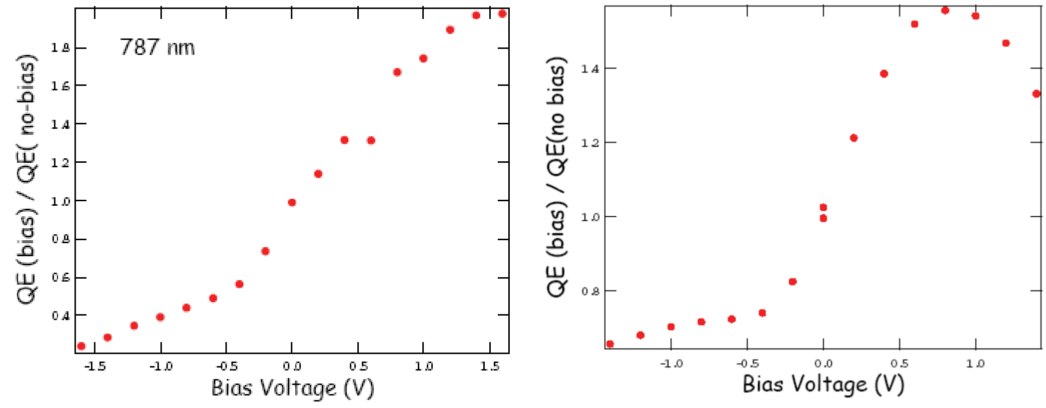

FIGURE 4. Increase of the quantum efficiency of samples 18A [left figure] and 19B [right figure] with applied voltage when positive bias is applied on the cathode surface. The samples where illuminated with a 787nm laser.

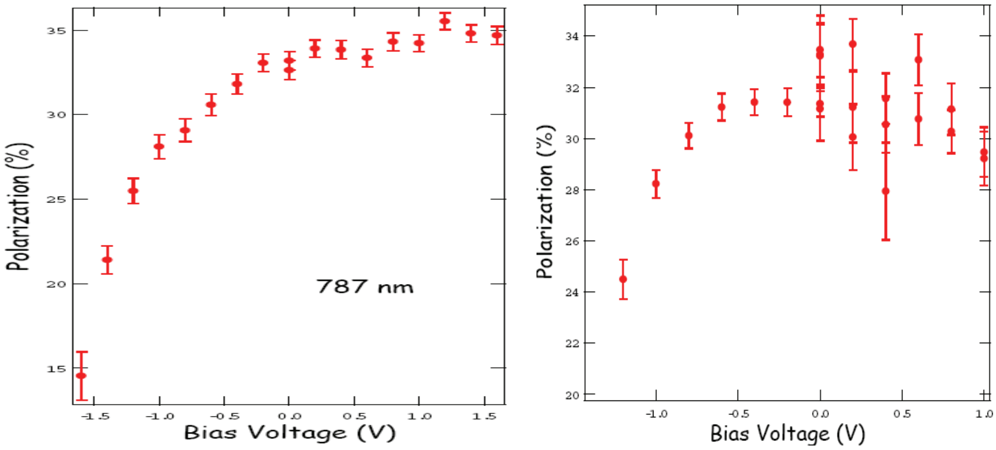

FIGURE 5. Increase of the polarization of samples 18A [left] and 19B [right] with applied voltage when positive bias is applied on the cathode surface. The samples where illuminated with a 787nm laser.

CONCLUSIONS

As seen in Figs. 4,5, both the QE and polarization of the photocathodes are increased with positive bias at the cathode surface by a factor of up to1.8 and 1% respectively.

Both the QE and polarization increase during forward bias at the cathode surface because the electrons have shorter transit time in the active region and scatter less both in the active region and the BBR.

Further improvements in observing the bias effect on the QE and polarization can be achieved by fabricating more stable Schottky contacts at the cathode surface (e.g. by depositing a Re grid) and using samples with high polarization such as strained GaAsP/GaAs superlattices.

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