PROSPECTS FOR SIGNIFICANTLY HIGHER ELECTRON POLARIZATION

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1. Importance of Higher Polarization

For left-right asymmetry measurements, the error on the theoretical asymmetry after \( N_{tot} \) events is

\[
\Delta A_{LR} = \left[ A_{LR}^2 \left( \frac{\Delta P_g}{P_g} \right)^2 + \frac{1}{P_g^2} \frac{1}{N_{tot}} \right]^{1/2},
\]

where \( P_g \), the beam polarization, is typically 0.7 to 0.85 depending on the details of the polarized electron source and the accelerator pulse profile. Thus a fractional increase in the value of \( P_g \) will reduce the statistical error twice as fast as the same fractional increase in the value of \( N_{tot} \).

In addition, since right-handed electrons, \( e_R^- \), have no weak interaction, their behavior is distinctly different than left-handed, \( e_L^- \). For processes that have a strong dependence on polarization, the degree of polarization is expected to be an important component in the discovery threshold.

Indeed, certain polarization-dependent processes, such as production of \( W^+W^- \) pairs, have such enormous cross-sections that they dominate the backgrounds for many experiments. These backgrounds can be effectively suppressed using highly polarized beams. In particular, precision measurements of the properties of some SUSY particles may only be possible with significantly higher polarization beams than have typically been available.
Fig. 1. Examples of acoplanarity distributions for smuon pair production with (a) unpolarized electron beam, and (b) a 95% right-handed polarized beam. (Fujii 1996)

2. Three-Step Model

Limitations in polarization and yield for semiconductor photocathodes can be understood in the framework of the three-step model (Spicer 1958).

Fig. 2. Band structure for p-GaAs illustrating band-bending near surface.
Step 1. Absorption of photons in bulk material resulting in promotion of valence band electrons to the conduction band.

Step 2. Transport of electrons to the surface.

Step 3. Escape of surface electrons to vacuum.

In the figure, the heavily p-doped (bends bands downward at the surface) semiconductor material has a thin Cs-oxide overlayer to form an NEA surface.

3. Initial Polarization

The polarization $P$ can be expressed as a product of 3 factors, one for each of the 3 steps:

$$P = P_1 P_2 P_3,$$

where $P_1$ is polarization upon initial excitation to the CB, and $P_2$ ($P_3$) is the probability of escape from the active areas (BBR) without loss of polarization.

$P_1$ depends on: (1) the hh-lh band splitting, $\delta$, at the $\Gamma$ point, and (2) any variation in the band edges.

The band splitting is a result of strain induced by lattice mismatch. For single strained-layer (as used for SLC), perfect strain can only be maintained up to a critical thickness, $d_c$, which is ~10 nm. Beyond this, lattice dislocations caused in large measure by imperfect manufacturing methods result in gradual degradation of strain.

Single-strained-layer cathodes such as used for SLC have active layers with thickness, $d$, of ~100 nm. Short-period, strained superlattice (SL) cathodes that are under development consist of alternating quantum wells and barriers each of which is only 3-4 nm thick.

Using a SL design, one can expect an average $\delta$ on the order of 50 meV.

For highly-doped materials at RT, variations in band edges are dominated by band tailing, which is spreading of edge due to random potential fluctuations associated with the ionized acceptors (in p-doped material). Band tailing can be characterized by a parameter, $\gamma$, which from photoluminescence data has a value of ~20 meV for dopant density of $5 \times 10^{18}$ cm$^{-3}$ (typical SLC value). Broadly speaking, $\gamma \propto N_A^{1/3}$.

Initial polarization can be expressed as $P_1 = 1 - \delta P_1$ where $\delta P_1 \approx e^{-d \gamma}$. Thus for SLC dopant densities one expects $P_1 \sim 0.92$. One should be able to increase this to unity in a SL by a combination of lower dopant density or larger $\delta$, both of which are doable.
Fig. 3. Crystal lattice, energy level diagrams at the Γ point, and transition probabilities for (a) unstrained GaAs, and (b) strained GaAs on GaAs$_{0.72}$P$_{0.28}$. The constants shown are for room temperature. In (b) the heavy-hole (hh) valence band is separated from the light-hole (lh) at Γ by δ. On the right, only transitions for e$^-$ excitation are shown. The resulting polarizations assume near-threshold excitation.

4. Depolarization During Transport to Surface

In general $P_2$ affected by two depolarization components: (1) depolarization during thermalization to bottom of CB, and (2) depolarization during diffusion to the surface. The first is irrelevant in our case (excitation at threshold).

For nearly degenerate p-doped materials at RT, spin relaxation during step 2 dominated by the exchange interaction between CB electrons and the bound holes. This is known as the BAP mechanism. (Bir, Aronov, Pikus 1976).
Given by \( P_2 = \frac{\tau_s}{\tau_s + \tau} \), where \( \tau_s \) is the spin relaxation time and \( \tau \) is the electronic lifetime. If \( \tau/\tau_s \ll 1 \), then \( P_2 = 1 - \delta P_2 = 1 - \tau/\tau_s \). Since \( \tau = \frac{d}{S_1 + S_o} \) where \( S_1 \) (\( S_o \)) is the heterointerface (surface) recombination velocity, and assuming \( S_1 \ll S_o \), the expression for \( P_2 \) simplifies to

\[
P_2 \approx 1 - \frac{d}{S_o \tau_s}.
\]

Typical values (assuming an SLC dopant density) are \( S_o = 2 \times 10^6 \) cm/s and \( \tau_s = 5 \times 10^{-11} \) s, predict \( \delta P_2 \approx 0.1 \).

Since for the BAP mechanism, \( \tau_s \) varies inversely with \( N_A \), \( \delta P_2 \) will be essentially zero if \( N_A \) in the bulk is reduced by at least an order of magnitude.

Reducing \( d \) will in general reduce the QE, so this is not a real alternative.

### 5. Depolarization in Band-Bending Region

Electrons spend a long time in BBR before emission to vacuum. BAP mechanism not applicable because of hole depletion.

The predominant depolarization thought to be diffusion of spin precession vector or “DP” mechanism (D’Yaknov and Perel’ 1971), which is quite sensitive to K.E.

Energy distribution of e\(^-\) emitted to vacuum a broad plateau from just below the CBM in bulk to vacuum level.

Energy resolved polarization measurements show polarization first decreases with decreasing energy, then levels off.

Explanation is that e\(^-\) reaching low K.E. fall into localized fluxuation states associated with fluxuation potential generated by random impurity distribution. Energy where localization begins known as percolation level (PL).

To minimize depolarization, need to keep K.E. low. For this want PL high, which requires high dopant density (which is also prescription for increasing the saturated current).

Solution is to use gradient doping. How effective this will be in reducing the depolarization in the BBR is not well known at present.

### 6. Final Remarks

A partial confirmation. Polarization observed at SLAC to increase as QE decreases, i.e., e\(^-\) that have undergone simultaneous energy and spin relaxation in BBR are blocked.
The polarization rises from ~0.75 to ~0.85 as the QE decreases by an order of magnitude.

At the lowest QE, the value of $P$ should correspond to that of electrons just entering the BBR. Extrapolating this value to zero active-area thickness gives $P_i=0.95$, similar to what was predicted earlier.

**Conclusion.** Using a short-period strained superlattice structure combined with gradient doping, one should be able to achieve $P \geq 0.95$. 