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POLARIZED ELECTRON SOURCES*

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Polarized electron sources for high energy accelerators took a significant step forward with the introduction of a new laser-driven photocathode source for the SLC in 1992. With an electron beam polarization of >80% and with ~99% uptime during continuous operation, this source is a key factor in the success of the current SLC high-energy physics program. The SLC source performance is used to illustrate both the capabilities and the limitations of solid-state sources. The beam requirements for future colliders are similar to that of the SLC with the addition in most cases of multiple-bunch operation. A design for the next generation accelerator source that can improve the operational characteristics and at least minimize some of the inherent limitations of present sources is presented. Finally, the possibilities for producing highly polarized electron beams for high-duty-factor accelerators are discussed.

I. INTRODUCTION

Polarized electrons have long been used in the study of atomic and condensed matter physics[1]. With the development of high-energy electron accelerators, the possibility to study nuclei, quarks, and gauge bosons using polarized electrons presented itself. The first polarized electron source to be used for a modern accelerator was an atomic-beam source in which a state-selected beam of atomic Li was photoionized by intense light from a pulsed lamp[2]. This source, which began operating at SLAC in 1974, produced the desired 1.6-μsec pulse at 180 pps with high polarization P_e, on the order of 85%, but the maximum current in the pulse was typically ≤0.25 mA, well below the accelerating capability of the linac. Although this intensity was roughly matched to what the target for the high-energy electron beam could accommodate, the electron spin direction could be reversed only slowly by reversing a large magnetic field, which introduced many unwanted effects, and most importantly, the source, even after several years of intermittent operation was very difficult to operate and relatively unreliable. The operational efficiency of the atomic-beam source at SLAC over a several year period was ~50% at best. A similar atomic-beam source using Cs but based on the Fano effect was developed during this same period for the Bonn synchrotron.

Although there were several other types of sources under development in the 1970s, the real breakthrough came following the suggestion in 1974[3] that GaAs, a III-V semiconductor with interesting properties, might prove to be a good polarized electron source. Photoemission from GaAs treated to have a negative electron affinity (NEA) surface was known to be an efficient process, the quantum yields ranging well above 10%. Photoluminescence studies had also demonstrated that if the incident light were circularly olarized and monoenergetic with a wavelength corresponding to the near band-gap energy, the electrons promoted to the conduction band in the solid would be polarized at or just below 50%. Following the initial suggestion, it was quickly shown that there is no significant depolarization when extracting the electrons from the solid. Although the expected polarization from unstrained GaAs is lower than for the atomic-beam sources, the intensity promised to be limited only by the energy of the light source, the polarization direction should be reversible optically, and the operational characteristics of a solid-state source promised a high degree of reliability.

At SLAC, a GaAs source was quickly built and successfully operated in 1978 for a high-energy physics experiment[4]. For this experiment, 1.6-μsec pulses with currents up to 15 mA were accelerated at 180 pps. P_e measured at high energy was ~37%. With two photocathode guns available during the experiment, the operational efficiency during each session was ~75%, a significant improvement over that for the atomic-beam source.

At Bonn, the Fano source was soon dropped in favor of a GaAs source, and other laboratories, such as MIT/Bates and Mainz, also installed GaAs-type sources for their electron accelerators. These latter two accelerators in particular saw extensive polarized beam operation in the late 1980s, while there was a long hiatus of polarized beams at SLAC from 1981 until three years ago.

With the commissioning of a new GaAs source for the SLC in 1992, a new era of highly reliable polarized-beam accelerator operations began. The polarization of this source has increased to the level of 80-86%. The source and its performance will be described below. The operational aspects of the SLC source are extremely well-matched to the SLC capabilities. For the most part, this performance should be repeatable for the NLC/JLC. The reservations implied here concerning suitability for operation of future colliders will also be discussed below.

A major limitation of GaAs sources has proven to be operation at high polarization for a high-duty-factor accelerator. The possibilities for overcoming this limitation are also discussed.

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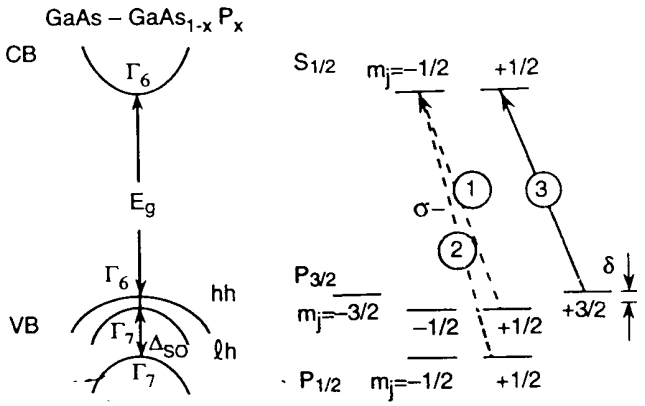

Figure 1. Energy level diagram and transition probabilities at the Γ point for a strained-lattice GaAs cathode.

II. PRODUCTION OF POLARIZED ELECTRONS FOR HIGH PEAK-CURRENT ACCELERATORS

A. GaAs sources

The process by which highly polarized electrons are produced in strained-lattice GaAs is illustrated in Figure 1. At the left of the figure are shown the energy bands at the Γ point. For direct band gap semiconductors such as GaAs, the valence band (VB) maximum and conduction band (CB) minimum are aligned in momentum space at the Γ point, allowing optical transitions between energy bands that follow the angular momentum selection rules for optical transitions in atoms. The transitions for illumination with left circularly polarized light (σ-) are shown on the right of Figure 1 for photon energies between the band gap (E_g) and $E_g+\Delta_{so}$, where Δ_{so} is the energy separation of the spin-orbit split-off band. The relative transition rates are in circles. A small energy difference, δ, can be introduced into the $P_{3/2}$ substates by applying a strain in the growth direction of the crystal. The $m_j=\pm3/2$ substates will be higher in energy than the $m_j=\pm1/2$ if the strain is tensile. With sufficient strain, if the energy of the excitation photons is further adjusted to be between E_g and $E_g+\delta$, only the transition shown by the solid line is allowed, and consequently the polarization can in principle be 100%. The most successful technique developed so far for producing the desired strain is to grow a thin layer of GaAs on a sublayer material that has a slightly smaller lattice constant[5]. The high-polarization cathodes now used at SLAC consist of a 100-nm layer of GaAs, p-doped to 5×10^{18} cm^{-3}, grown by MOCVD on a sublayer of GaAsP[6]. The wavelength dependence of the polarization and QE of a high-QE SLAC cathode is shown in Figure 2. The wavelength dependence of the QE is primarily related to the rapid drop in optical absorption as the band gap is approached. There is a small QE dependence of the polarization peak as illustrated in Figure 3. Since the higher polarizations are correlated with very low QE, when the surface most likely has a positive electron affinity (PEA), the presumption is that the CB electrons originating away from the surface undergo some depolarization, either as they lose energy while thermalizing, or while they diffuse to the surface. For low QE, the PEA condition allows only electrons promoted near the surface (so called "hot electrons") to be emitted to vacuum.

The electrons that are excited into the conduction band can be extracted efficiently by creating an NEA surface. First the p-doping of the crystal lowers the energy bands at the surface by as much as half the band gap. This is a significant effect for large-band-gap semiconductors. Coating an atomically clean surface with a layer of Cs and an oxide (at SLAC, NF_3 is used) at the level of a monolayer or so will then lower the work function below the CB level in the bulk of the crystal. The clean surface is achieved by heating the crystal to 600°C for ~1 hour. The heat-cleaning plus application of Cs and oxide is said to "activate" the surface. The diffusion length for minority carriers in the CB of GaAs is on the order of 1 μm at room temperature, while the optical absorption depth near band gap is slightly larger. Thus when even a modest negative bias is applied to the crystal, a very high percentage of the CB electrons are emitted to vacuum.

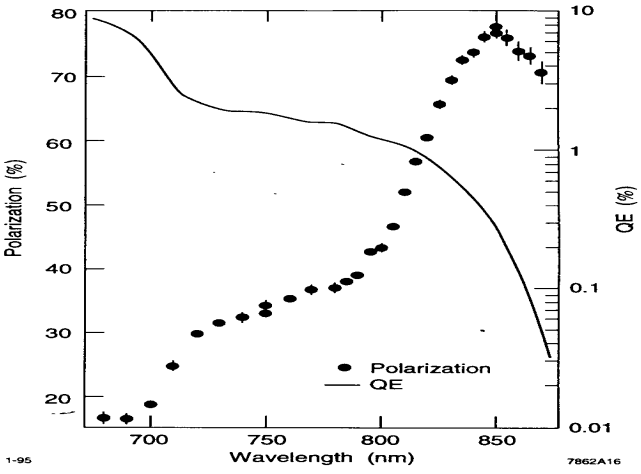

Figure 2. P_e and QE for a SLAC 100-nm strained-lattice cathode as a function of the excitation wavelength, measured at room temperature. See [10].

Since the QE scales roughly as the crystal thickness normalized to the diffusion length, the QE is considerably reduced in the thin cathodes. Nonetheless, with one important limitation to be discussed next, it has been found that the charge that can be extracted scales simply with the laser pulse energy up to the space-charge limit of the gun. The band gap for the strained-lattice cathodes is about 850 nm. The tunable, Q-switched, cavity-dumped, Ti:sapphire laser system for the SLC produces pulse energies up to and

exceeding several hundred microjoules. Since the SLC requires about 10^{11} e^- per micropulse at the source, this implies sufficient photons for a QE as low as 0.01%, whereas the typical operating QE is ~0.1%. These high laser energies are for single pulses and at rather low repetition rates. The repetition rate is presently limited by the lasers available for pumping the Ti:sapphire[7].

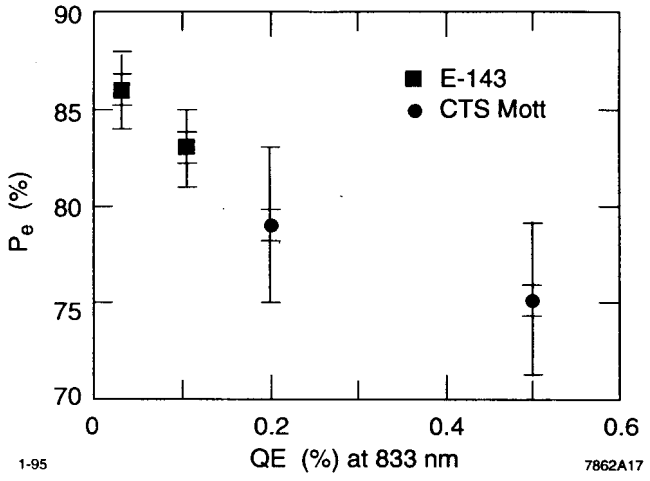

Figure 3. Polarization at the polarized electron source as a function of QE. See [10].

B. Cathode emission limitation

The exception to the scaling rule occurs when one attempts to extract a large amount of charge in a short interval (high peak current). Negative charge tends to build up at the surface during extraction due to the presence of surface states. At a certain point the discharge process for this buildup falls behind, and a surface barrier begins to grow until equilibrium is again established[8]. The surface barrier may arise quite rapidly, perhaps on the picosecond level, while the discharge can be much slower, on the nanosecond level and perhaps even containing microsecond-level components. The cathode charge limit scales roughly as the QE. For the SLAC cathodes, the charge limit for a QE of 0.1% at the polarization peak is about $5x10^{10}$ e^- cm^{-2} in a 2-ns pulse. The discharge time is about 100 ns. Since separate Ti:sapphire lasers are used to produce the two SLC microbunches, the second laser is tuned to a much higher photon energy (since the second electron bunch need not be polarized), for which the QE and charge limit are both high. Thus the second bunch can be matched in intensity to the first.

A principal factor affecting the discharge rate is the dopant density. If the density is increased to ~$2x10^{19}$ cm^{-3}, the discharge time decreases to about 10 ns. However, higher densities seem to result in lower polarization. The solution to the emission limitation problem may be to increase the dopant density at the surface while (possibly) lowering it in the bulk. Since high-temperature heat cleaning removes the surface layer (and also results in diffusion of the dopant material from the surface into the bulk), a cathode preparation technique that avoids high temperatures is essential for this solution.

Although the motivation here for suggesting a differentially doped cathode is to reduce the emission-limiting effect of the surface-charge buildup, obvious benefits in addition are higher QE at all emission levels (due to increased band bending at the surface) and possibly higher polarization (if the dopant density in the bulk is reduced). Differentially-doped, strained-lattice GaAs cathodes of the SLAC type should produce a stable polarization of at least 85-90% polarization at all QE levels[9].

C. The SLAC polarized electron source

Because of the high operating cost of accelerators, it is extremely important that the source operate reliably. The present polarized electron source[10] for the SLAC linac has operated for the past 3 years (2.4 years of equivalent full-time operation) with >95% efficiency overall, where operating efficiency is defined as the percentage of time the source is operating or able to operate upon demand with nominal beam during all scheduled accelerator operating time. The principle factors contributing to the reliability of the SLAC source are:

1) Careful design of the gun to provide a base pressure of ~10^{-12} Torr exclusive of H_2;
2) Differential pumping between the gun and the downstream vacuum system;
3) A 38° bend, 1-m downstream of the gun, which isolates the cathode from reflected or reverse accelerated electrons;
4) Careful design of the electron optics to reduce beam interception in the first meter to <0.1%, and in the first 3 meters to <1%;
5) Incorporation of diagnostics to measure the beam interception to the level of 0.1%;
6) Providing the required field gradient at the crystal (1.8 MV/m) while keeping the maximum gradient along the cathode electrode ≤7 MV/m;
7) Processing of the high voltage (120 kV) for the cathode bias to reduce dark current to <50 nA DC as read by a nanoammeter floating on the high voltage terminal of the gun;
8) Backup guns;
9) A means to install and remove activated GaAs crystals without breaking the gun vacuum (load lock); and
10) A reliable tunable laser with a stable laser beam transport system.

The source uses a conventionally designed gun in which the cathode electrode is supported by a large ceramic insulator that also provides a major portion of the vacuum wall. The laser beam enters, and the emitted electrons exit, through a hole in the anode. The load-lock system for inserting the activated GaAs crystal into the gun after the vacuum bake of the gun chamber and after the high-voltage processing is essential for a gun that is to be operated at high voltage, otherwise the processing irreversibly destroys the QE of the cathode. In addition, the QE that can be achieved when the GaAs is not in the gun during the vacuum bake of the chamber is typically higher by a factor of ~2 and is more reproducible. Although SLAC now has 4 interchangeable photocathode guns, the guns have only been changed between accelerator operating cycles.

Table 1. Operating characteristics of SLAC polarized electron source for 1994-5 SLC run.

SLC operating time	~230 days
Beam structure at source	Two 2-ns pulses, 60 ns apart, at 120 pps, $7x10^{10}$ e^-/pulse
Source operating efficiency	>99%
Cathode	100-nm strained-layer GaAs
Cathode bias (gradient)	120 kV (1.8 MV/m)
Active area of GaAs	1.5 cm^2
Typical QE	0.1% at polarization peak
QE lifetime (1/e)	1200→300 hours
Number of cesiations	~50
Time between cesiations	4 days typical
Polarization, P_e	~80% at 845 nm
Excitation wavelength	845 nm at 0°C

Typical operating characteristics of the SLAC source for the 1994-5 operating cycle of the SLC are illustrated in Table 1. The only task necessary to perform on the gun during the entire 10 months of continuous operation (if the time provided for other accelerator operations is included) was to periodically apply a small amount of Cs to the cathode, a computer controlled process (initiated by the accelerator operator) that took ~20 minutes. The required charge of $7x10^{10}$ e^- per microbunch was only slightly below the peak charge (8-$9x10^{10}$ e^-) following a full application of Cs to the cathode. To maximize the polarization (see Figure 3), only enough Cs was applied to give 3-5 days of operating time between cesiations[11]. Once the run began, there were no more cathode activations and no more NF_3 was applied.

III. POLARIZED SOURCE DESIGN FOR THE NEXT GENERATION OF LINEAR COLLIDERS

The SLC source already meets most of the requirements for NLC/JLC. The principle remaining tasks are to develop the proper light source, and also to eliminate or avoid the effect of the charge limit.

A. Laser requirements

If we assume the beam requirement is a train of 100 micropulses spaced by 1.4 ns, each with a charge at the interaction point of $1x10^{10}$ e^-, then the total charge required at the source is about $1.5x10^{12}$ e^- per macropulse if generated by an optical pulse train. With present technology, one should be able to generate such a train with the required macropulse stability of 0.5% rms[12]. The present SLAC approach is to use a resonant Pockels cell driven at 714 Mhz to chop (50% duty cycle) a long laser pulse. The required laser energy (5 kW for 140 ns) can be produced using a Q-switched laser with a sufficiently long optical cavity.

B. Charge limitation effect

While the selection of a laser for the NLC source can be considered a technical problem whose solution is foreseen, the charge limitation is an inherent property of the semiconductor crystals presently in use at SLAC. A new design for the cathode structure which eliminates or avoids the charge limit must not sacrifice polarization. A high QE must also be maintained.

The emission limitation is not a problem if the total charge to be extracted within the discharge time is considerably less than the charge limit. The active area of a SLAC cathode has been increased to 3 cm^2, resulting in a charge limit for a 0.1% cathode (medium doped) of ~$1.5x10^{11}$ e^- in 2 ns. This limit increases beyond the space-charge limit of the gun (about $2x10^{11}$ e^- in 2 ns) if the dopant density is increased to $2x10^{19}$ cm^{-3}. For the NLC source, the total charge to be extracted in 10 ns is ~$1x10^{11}$ e^-, which at most is half the charge limit. Nonetheless, the charge limits for medium- and high-dopant densities need to be measured using laser pulses in the range of 10 to 100 ns.

C. Gun design

Although the SLAC gun has performed exceptionally well, the requirement that the load-lock mechanism float at the high voltage of the cathode bias is awkward at best, resulting in unnecessary complications when using load lock. A more compact gun design that places the high voltage insulators inside the grounded gun vacuum structure (the "inverted-geometry" design) is shown in Figure 4. A gun of this design has been built at SLAC[13] with an electrode design similar to that of the accelerator gun. The load-lock mechanism can be removed during gun operation if desired, but if left attached would is at ground potential. This gun design is a very promising candidate for a next-generation GaAs source.

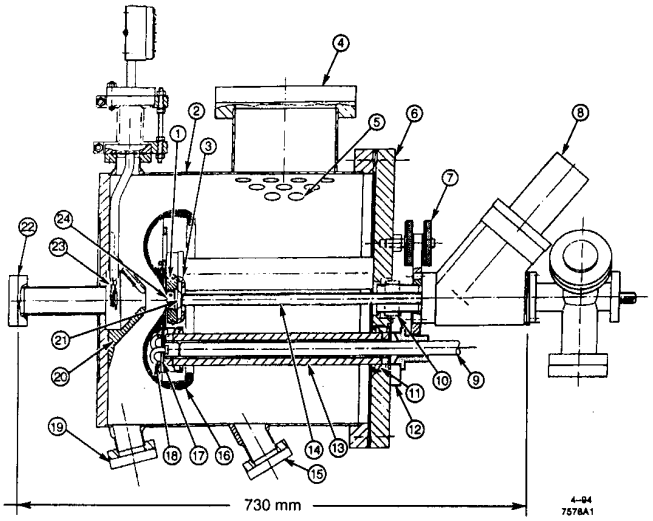

Figure 4. Cross section of the SLAC inverted-geometry gun. The electrons exit from the cathode (16) to the left through the anode (20). One of the 3 high voltage insulators is shown at (13). The cathode insertion tube (withdrawn when producing electrons) is shown at (14). For the remainder of the components, see [13].

IV. HIGH POLARIZATION ELECTRONS FOR HIGH DUTY FACTOR ACCELERATOR

The duty factor (DF) of the SLAC linac ranges from $2x10^{-4}$ for long pulse operation to $5x10^{-7}$ for SLC. For the SLC design performance, the source is required to generate a peak current I_p of ~10 A (an average current I_A of I_pxDF=4.8 μA). For linac operations with 1.6 μsec beam pulses, the source has produced an I_p of 30 mA (thus an I_A of ~6 msec).

The pulse width for lasers cannot be extended much beyond the tens of microseconds, and certainly not for high repetition rates. As the pulse width is increased, the maximum possible power also decreases. Thus, photocathode sources for high-duty-factor accelerators use cw lasers. Tunable cw lasers are at present limited to a few watts of output power. A QE of ~2% is routinely achieved with sources employing thick, unstrained GaAs, making possible cw currents >10 mA. However, the *highest* QE achieved with the SLAC high-polarization cathodes has been about 0.2%, with 0.1% being typical. This implies a maximum cw current of ~1 mA. (It should be noted that long lifetimes of the cathode QE may be difficult to achieve for such high average currents.)

Several possibilities exist for producing higher cw currents using high-polarization cathodes. A GaAs-AlGaAs superlattice design has been shown to give ~70%. polarization at ~750 nm and, using a load lock, a QE of over 2%[14].

A second possibility is a distributed Bragg reflector (DBR) strained-lattice cathode[15]. In principle this cathode can enhance the optical absorption efficiency by nearly an order of magnitude.

The QE of the simple strained-lattice cathodes can presumably be increased substantially by applying a high-dopant density to the surface, as was done for the superlattice mentioned above, and as was discussed earlier in this paper. If successful, such a cathode might still benefit from the addition of a DBR.

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