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Polarized RF Guns*

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INTRODUCTION

Since their initial introduction in 1985 at LANL by Fraser, Sheffield, and Gray (1), rf photoinjectors have made rapid progress. Because of the strong acceleration of the beam in the first rf cavity, the effects of space charge are quickly reduced with the result that beams of up to several nanocoulombs per bunch can be readily produced with low emittance. In addition, since the electrons emitted from the cathode generally follow closely the pulse shape of the optical source, pulse shaping is readily accomplished with the optical beam, allowing single- and multi-bunch formation over a wide range of parameters. These features have made rf photoinjectors popular for a variety of applications today including free electron lasers (2).

Given the unique properties presented by photocathode rf guns, it was realized very early that such an electron source would be ideal for linear colliders if the beam could be polarized (3). Present collider designs typically require a fairly complex pulse train with a reasonably low emittance. RF guns for this purpose are already being used for

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the TESLA Test Facility (TTF) at DESY and for both the drive and probe beams of the CLIC Test Facility (CTF) at CERN. However, the primary electron beam for colliders must be polarized (4). Polarized electron sources for accelerators have also made rapid progress. Since the introduction of the polarized source for the SLC at SLAC in 1992, the world's first linear collider has operated exclusively with a polarized electron beam, resulting in >30,000 hours of beam time with >95% availability of the source (5). The SLC source utilizes a dc-biased gun with a solid-state (GaAs or its derivatives) photocathode. Today, all linac-based polarized electron sources are of a similar design (6). The success of the SLC source is directly correlated with the achievement of an extremely good vacuum environment for the cathode, both during the cathode activation (which is done in a separate vacuum chamber) and during the source operation.

Because of its high quantum efficiency (QE) in the visible, GaAs was actually considered as a possible cathode material for the first rf photoinjector (7) but rejected because of multiple concerns. The concerns expressed at that time included the sensitivity of GaAs to the vacuum environment and the emission time of the photoelectrons. Extensive discussion of using GaAs in an rf gun did not begin until 1993 at the Workshop on High Intensity Electron Sources in Legnaro, Italy, where two papers were presented with proposals for such a source based on the achievements of both rf guns and polarized dc guns (8). The Legnaro workshop was followed soon after by SOURCES '94, organized by DESY to examine electron and positron source possibilities for future linear colliders. At the time there was some excitement concerning the possibility that a polarized rf gun might obviate the need for an e^- damping ring for TESLA. However, the final recommendation of the relevant working group was that the impact of lower emittance on the cost and performance of damping rings needed further study (9).

Assuming that a polarized rf gun could be successfully produced and operated, what would be its advantages compared to a dc polarized gun plus rf compressor? The principal advantage is that an rf photoinjector produces an inherently lower beam emittance. While for a collider this emittance is not low enough to eliminate the electron damping ring, it will certainly simplify both the damping ring and the intervening beam transport system. Because of the rapid acceleration to high energy, bunch shaping is much more feasible and can be used to further reduce the beam emittance. Since the transmission will be higher, the charge required to be extracted is reduced by up to a factor of two, mitigating the restrictions of the cathode charge limit (10). The QE will also be higher (due to the Schottky effect), reducing the demands on the source laser system. Finally, beam-loading compensation is somewhat more effective and certainly more straightforward for an rf gun.

ACTIVATED GaAs CATHODES

GaAs is a direct-gap III-V semiconductor that crystallizes in the zincblende structure. The energy levels and transition probabilities in the vicinity of the Γ point are shown in Fig. 1. At the band-gap minimum there is a two-fold degeneracy of the valence band (VB) maximum at which the heavy-hole (hh) and light-hole (lh) bands are mixed. The

VB maximum has $P_{3/2}$ symmetry while for the conduction band (CB) minimum it is $S_{1/2}$. Therefore if circularly polarized light is used that is at least the energy of the band gap, but less than the energy of the next lower VB, $E_g+\Delta_{SO}$, the electrons promoted to the CB will be highly polarized. For bulk GaAs the polarization, $P=\left(N^{+}-N^{-}\right)/\left(N^{+}+N^{-}\right)$, is limited to 50% as indicated by the figure. However it is possible to break the degeneracy of the VB maximum sufficiently to promote electrons exclusively from the higher of the hh or lh states, thus offering the possibility of up to 100% polarization.

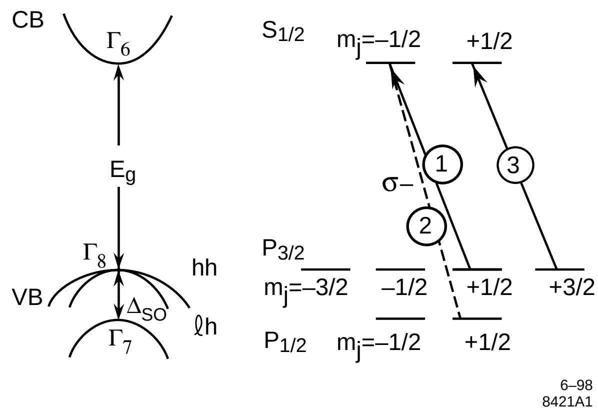

Figure 1. Energy level diagram (left) and transition probabilities (right) at Γ point for bulk GaAs. Only the transitions for left circularly polarized light (σ-) are shown. The solid-line transitions are for $E_g < \left(E_g + \Delta_{SO}\right)$.

For use as a photoemissive material, the GaAs crystal is typically heavily p-doped, which results in band bending at the surface. The electron affinity, χ, defined as the difference between the vacuum and the CB minimum at the surface, is about 4 eV for a clean surface with flat bands. Activation of the GaAs surface requires depositing approximately a monolayer of an alkali (usually Cs) and an oxide (usually O_2 or F) on the atomically clean surface, resulting in a reduction of χ to nearly zero. During the deposition of the (Cs,O) layer, the surface of the p-GaAs becomes positively charged, repelling the positively-charged holes near the surface but not the distributed negatively-charged ionized acceptors, resulting in a high field that bends the band edges down at the surface by as much as a third of the band gap. Since the band gap for GaAs is about 1.4 eV at room temperature, this results in a negatively electron affinity (NEA) surface that greatly enhances the probability of photoemission. The photoemission process from an NEA semiconductor is usually described using the three-step model, which is illustrated in Fig. 2.

PROBLEMS AND ISSUES

In addition to vacuum and emission-time issues that were noted very early, outstanding problems that have been identified include the effects of dark current and rf breakdown on the QE of the cathode, the effect of the rf on the electron polarization, the effect of an activated GaAs crystal on the rf performance of the cavity in which it resides, and the question of the charge limit under conditions of very short, high-intensity optical excitation.

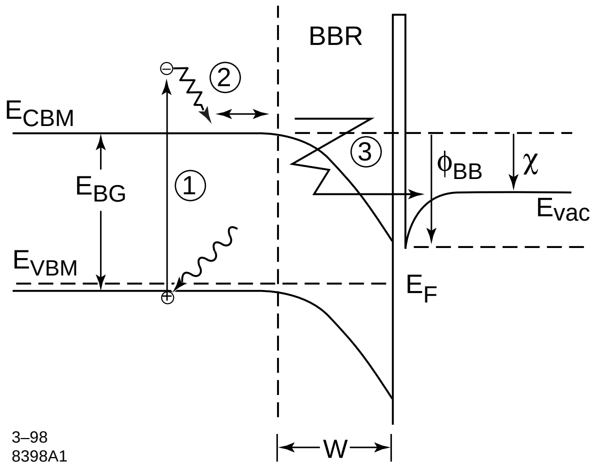

Figure 2. Schematic energy diagram near the surface for GaAs illustrating the three-step emission process where step 1 is absorption of a photon creating an electron-hole pair, step 2 is the thermalization and diffusion of the conduction band electron to the band bending region (BBR), and step 3 is the emission of the electron to vacuum. E_{VBM}, E_{CBM} and E_{vac} are valence band maximum, conduction band minimum, and vacuum level energies respectively. E_{BG} is the band gap, E_F the Fermi energy, χ the electron affinity, and W and ϕ_{BB} the width and depth of the BBR respectively.

It is well known that the QE of an activated GaAs crystal can be maintained only in an extremely good vacuum. For a QE lifetime on the order of a few hours, a vacuum of at least 10^{-10} Torr is required. The SLC source, which has achieved lifetimes of several thousand hours under SLC operating conditions, maintains a vacuum of 10^{-11} Torr that is entirely dominated by H_2. Some gas species that are commonly found in high vacuum systems such as CO are relatively benign, while O_2, CO_2, and H_2O are especially harmful. Many of the most common background gases are pumped by the excess Cs on the GaAs surface following an activation. Although the details of how the initial (Cs,O) layer is formed are important, it appears that the thickness of the layer can be increased many fold without any detriment to performance. In fact, periodically adding a small amount of Cs to the surface is a common technique used with dc guns to restore the initial QE. Following the initial activation, the QE for a GaAs cathode drops with time. For the SLC source, up to about 50 re-cesiations have been applied without re-activating and without adding any additional oxide, each re-cesiation completely restoring the initial QE. Assuming no loss of Cs from the cathode surface (11), the 50 re-cesiations represent the accumulation of ≤1 additional monolayer.

To prepare an rf or dc-biased gun for operation, it must be rf or high-voltage (HV) processed to eliminate rf or HV breakdowns respectively before the activated semiconductor cathode is installed. This is readily done if the cathode is activated in a separate chamber, then installed in the gun maintaining a vacuum by using a "load-lock" system. RF guns generally require additional processing to reach the highest rf fields whenever a new cathode is installed. To preserve the QE of a newly installed

GaAs crystal, a cathode-plug design must be found that eliminates this additional processing.

Once a gun is operational, there is some level of dark current, defined as the average current emitted when the extraction voltage (dc or rf) is on but the laser beam is off. Surfaces other than the photoemitter surface can and do contribute to the total dark current. For a dc gun, the dark current is easily measured by noting the average current drawn from the HV power supply with the laser off. In the case of the SLC source, dark currents of >100 nA has been found to destroy the QE within a few hours, while <20 nA has almost no effect on the QE. External dark current is easily measured using downstream charge monitors. Internal dark current, meaning electrons that are both field emitted and re-absorbed inside the gun cavities, is more difficult to measure. High levels of dark current can be observed in the beam loading on the reflected rf pulse signal.

Band bending at the surface for p-GaAs is about 0.5 eV while the width of the band-bending region (BBR) for a dopant density $>2\times10^{19}$ cm^{-3} is <5 nm, resulting in an internal dc field >100 MV/m but confined to the BBR. By contrast, rf fields will penetrate well beyond the BBR. Since the conductivity of even highly-doped GaAs is less than that of Cu, the skin depth, which is inversely proportional to the square root of the conductivity, will be on the order of tens of micrometers at 3 GHz, but still considerably less than the ~1-mm thickness of the crystal (12). Thus a polarized rf gun may constitute a field-assisted photoemitter that will result in both enhanced emission with a shorter bunch length and also possibly higher polarization (13).

The bunch length of the electrons extracted from an rf gun should be kept below about 20° of rf phase. This is important not only to maintain a low emittance beam but also to minimize both loss of electrons during acceleration and also backward acceleration into the photocathode. However, the delay between promotion and emission in a semiconductor can be on the order of nanoseconds. For an NEA semiconductor, the emission time is governed by the diffusion time for electrons in the conduction band. One can easily calculate the time, t_D, for an electron promoted to the conduction band to diffuse to the surface from a depth of x within the epilayer:

$$t_D = \frac{x^2}{D}, \tag{1}$$

where D is the electron diffusion constant. If a conservative value of $D \approx 50$ cm^2 s^{-1} for GaAs at room temperature and a starting depth equal to one optical absorption length, $l_a \approx 0.7$ μm at 750 nm, are assumed, then t_D should be ~1 ns. For a thin epilayer of 100 nm, ~2 ps would be expected.

The cathode charge limit measured with the SLC source is ~4 A cm^{-2} for an extraction field of 1.8 MV/m, a dopant density of 5×10^{18} cm^{-3}, and a QE of ~0.25% at the polarization peak (14). At low fields, the charge limit increases linearly with field. If this relationship holds for high fields, then the charge limit for a field of 30 MV/m (see final section) should be on the order of 65 A cm^{-2}. The charge limit imposes a severe restriction on the product of bunch length and cathode radius. Based on a limit of 65 A cm^{-2}, extracting 1 nC of charge in 20 ps would require the cathode radius to be ≥5 mm.

REVIEW OF R&D PROGRESS

Up to the present there has not been a successful demonstration of photoemission from an activated GaAs cathode using an rf gun. However there has been experimental progress with most of the problems and issues outlined above, including major advances with vacuum and emission-time issues.

Recently-built S-band guns have pressures (at the ion pumps) after rf processing of about 10^{-10} (10^{-9}) Torr with rf off (on). Dark currents on the order of 1 nC per μs of rf (after filling cavity) are typical for conventionally cleaned S-band guns operating at ~130 MV/m (15), which would result in >100 nA average dark current at 180 Hz. At KEK it has been demonstrated that the dark currents from test cavities that are specially cleaned with high-pressure ultra-pure water (UPW) and then assembled in a Class 100 clean room can be reduced to ~130 (~13) pC/(μs of rf) at 130 (90) MV/m (16). More recently, field emission dark current from Cu electrodes–fabricated from Class-1 Cu using hot isotatic pressing (HIP), then electro-polished and UPW rinsed–has been reduced to the level of 1 nA for a dc field of 28 MV/m (17).

A complete GaAs test requires an rf gun equipped with a load-lock and an associated activation chamber. A relatively high-power pulsed laser tuned to a wavelength between 750 and 850 nm is also required although initial tests can use a pulsed laser system operating at shorter wavelength such as a doubled Nd:YAG or YLF. There are at present only two guns being used. Testing of GaAs cathodes has been underway at CERN since 1995 (18). The 1.5-cell S-band gun for the CTF drive beam is based on the BNL design. The gun and following booster section, which have been manufactured and assembled under clean room conditions (19), normally exhibits relatively low dark current. Since the gun was designed to be used with a Cs_2Te photocathode, it was already equipped with a separate activation chamber with a cesium source and a transporter for moving the cathode into the gun through a load-lock. For the initial tests, no attempt was made to activate the GaAs. The GaAs crystal, cut from a bulk-grown wafer with dopant density of 5×10^{18} cm^{-3}, was simply glued to an inset in the face of a detachable Mo nose for the rf plug using In as the glue. After chemical cleaning and a mild bake, the rf plug was inserted into the gun. Given the high dopant density, it is not surprising that the resonant frequency of the cavity was found to be unaffected. After vigorous processing of the first sample, a field at the cathode of 87 MV/m was achieved, but the cathode plug was later found to be seriously damaged as a result of the rf processing. At the maximum field, no dark current was detected, however from the light visible on a screen, an upper limit of 60 pC/(μs of rf) was estimated. For an S-band gun operating with a 2-μs rf pulse at 180 Hz, this limit corresponds to an average current of ~10 nA, well within the criterion mentioned earlier. A second sample, not activated but with a thin layer of Cs, was processed more gently to 60 MV/m without visible damage and again without detectable dark current.

At INP, Novosibirsk, a prototype S-band polarized rf gun has been constructed for the injector of the VEPP-5 complex (20). A cross section of this gun is shown in Fig. 3. As originally commissioned the base pressure of the gun was $<10^{-11}$ Torr. In the initial test the lifetime of a poorly activated GaAs cathode (QE~0.05%) was measured to be about

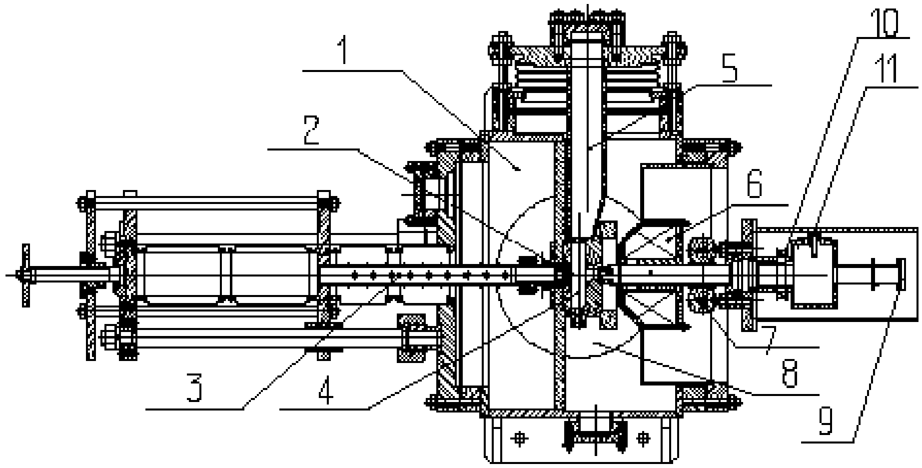

Figure 3. Cross section of the INP prototype polarized rf gun showing: 1) activation chamber, 2) photocathode assembly, 3) manipulator, 4) accelerating cavity, 5) waveguide, 6) focusing lens, 7) transverse corrector, 8) working chamber, 9) vacuum window for laser beam, 10) ceramic insulator, and 11) cavity for measuring bunch length. (From Aleksandrov et al., ref. 21.)

0.5 h. During the test, dark current for a field of 60 MV/m was observed to be about 2 orders of magnitude larger than for a clean cathode (21). In a later test, a well activated GaAs cathode (QE~5%) was inserted. In this case the dark current was high enough to completely kill the QE within a few rf pulses (22). Additional testing is planned.

Although the INP results are disturbing, there is actually no fundamental reason that an NEA semiconductor should field emit since there are essentially no free CB electrons when optical excitation is absent unless the external field is large enough to create an inversion layer at the surface. An inversion layer begins when the bands at the surface are bent downward to at least mid-gap. Since the behavior of highly-doped p-GaAs is similar to a metal, the additional bending necessary can be estimated from the usual Schottky-effect analysis. Assuming band bending of ~0.5 eV at low field, a weak inversion layer should begin at an external field of ~50 MV/m although rapid accumulation of free electrons would require significantly higher fields (23)!

The experimental determination of the level of field emission that can be attributed to an NEA photocathode in an rf gun is a complex problem because of uncertainties in the field emitting properties of the rf plug. Developing a technique to mount the crystal in an rf cell so as not to generate either rf breakdown or dark current is crucial. In preparation for a new set of tests at the CTF, a clever crystal mounting scheme–shown in Fig. 4–has been developed at SLAC (24). A slurry cutter is used to cut a "top hat" cross section from the original ~1-mm thick GaAs wafer with a precision of a few micrometers. The active surface can be installed parallel to the Mo face within a few milliradians if care is taken. The Ta leaf spring anticipates the effects of thermal expansion when the crystal is heat-cleaned as part of the activation process.

The latest tests at the CTF using this crystal-mounting scheme were conducted between November 1997, and January 1998 (25). There being no heat-cleaning capability in the CTF system, an attempt was made to clean the GaAs crystals by ionic

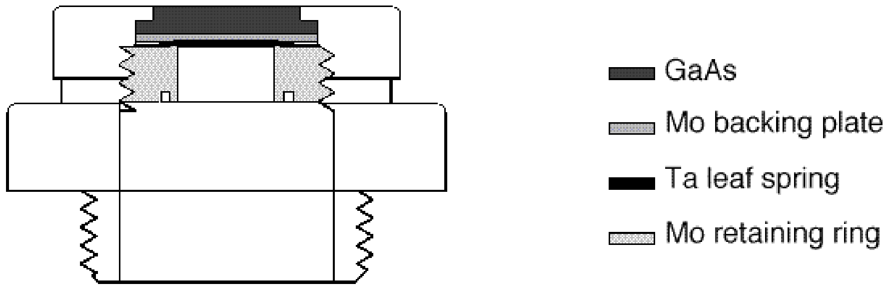

Figure 4. Cross section of Mo nose assembly for mounting GaAs crystal on end of cathode rf plug. The identified components are listed vertically in the order of their appearance in the cross section.

controlled etching (ICE), a technique developed at CERN for cleaning other types of cathodes (26). Unfortunately it was not possible to achieve a high QE. Nonetheless the cesiated crystals were again tested in the rf gun in fields up to 73 MV/m. In at least one case low-level dark current was observed only beginning at ~60 MV/m, and in any case was lower than observed for Cs_2Te crystals. Reliable performance with a non-activated cathode should be established before one can determine the added characteristics of an activated surface.

Recent measurements at Mainz of the electron photoemission time from a thin (epilayer of 150 nm), strained-layer GaAsP crystal indicate an emission time of no more than ~10 ps for the lowest charge (~0.5 fC) measured (27). The measurements were made using a dc gun biased at 100 kV. The crystal was illuminated by a 100-fs laser tuned to the polarization peak, which was at 836 nm. The laser spot diameter at the cathode was ~0.6 mm. The resolution of the rf analyzer was ~1 ps at 2.45 GHz. An observed increase of bunch duration with charge was attributed to an external space charge effect, but more recently the Novosibirsk-Legnaro group has shown that this effect is internal to the gun and is a current limitation not attributable to a gun space-charge effect (28). In fact the limit may be the same cathode charge limit described in refs. 5 and 10. The limit for the Mainz measurement, ~20 mA cm^{-2}, is only about a factor of ten below the limit found for the SLC source under similar conditions after scaling for differences in QE, epilayer thickness, and extraction field (29).

There is increasing evidence that the effect of the cathode charge limit can be greatly reduced by using a very high dopant density at the surface of the GaAs (30).

FUTURE POSSIBILITIES

Clearly much work remains to be done to establish the feasibility of a polarized rf gun. The resources required to build and test a new rf gun that would optimize polarization are sizable–well beyond the resources of most laboratories. An informal international collaboration of physicists from major accelerator laboratories was formed in 1996 to promote the investigation of the known problems and to maximize the use of existing resources (31). The GaAs testing at the CTF described above continues as part of this collaboration. In addition, the KEK-Nagoya group are utilizing the manufacturing and

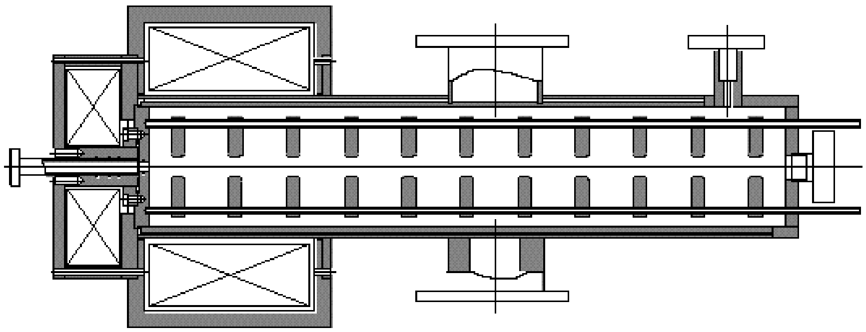

Figure 5. Cross section of the plane wave transformer S-band photoinjector being fabricated as part of an SBIR collaboration between UCLA and DULY Research. The cathode plug is on the left surrounded by the emittance compensating solenoid and the cathode field bucking coil. The rf feed and vacuum pump-out ports are in the center. An rf probe port is to the right. The laser beam enters and the electron beam exits at the far right end. (From Rosenzweig, ref. 32.)

assembly techniques developed to reduce dark current to construct a CERN-designed rf gun for use at the CTF. If the dark current proves especially low, this gun will be an excellent platform for testing an activated GaAs photocathode.

A promising candidate design for a future polarized rf gun is the plane wave transformer (PMT) S-band structure now being developed at UCLA (33). A cross section of the UCLA design is shown in Fig. 5. The features of this design that are appealing for operation with a GaAs photocathode are threefold. 1) The optimum transverse emittance is achieved with a peak accelerating field of 60 MV/m (minimum inversion layer) and a nominal launch phase of ~30° (reasonably high charge limit). For a carefully fabricated gun, this low field should essentially eliminate dark current and rf breakdown problems including those originating with the cathode plug. 2) The open structure allows more efficient vacuum pumping in the vicinity of the photocathode. 3) The volume between the disks and the outer wall increases the stored energy, which reduces the beam-loading problem for a collider multi-bunch photoinjector.

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