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Abstract

Normalized rms emittances well below 10^{-6} m (with thermal emittance ignored) are now predicted for a 1-nC, 10-ps, flattop beam using an S-band rf gun. The expected thermal emittance of a Cu cathode excited at 263 nm is shown to be ~0.3 x 10^{-6} m, which is potentially a serious limit on the overall minimum emittance. For GaAs, the photoelectron energy parallel to the emitting surface is now known as a function of the perpendicular energy. By adjusting the vacuum level for the semiconductor, it appears that the thermal emittance can be reduced (compared to Cu) by a factor of 2—even more if the cathode is cooled. The prospects for operating an rf gun with a III-V semiconductor photocathode such as GaAs are summarized.

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GENERATION OF LOW EMITTANCE BEAMS USING III-V SEMICONDUCTOR PHOTOCATHODES IN AN RF GUN*

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1 Introduction

Since rf guns operate with much higher extraction fields than traditional dc-biased guns, the space-charge forces near the cathode are dramatically reduced, making it possible to extract and accelerate very high-current low-emittance beams directly from the cathode. In addition, since the emittance from an rf gun is largely correlated, its growth can to a large extent be reversed by the application of a longitudinal magnetic field immediately following the cathode.

The operation of rf guns has received extensive theoretical treatment, and several simulation codes that take into account space charge have proven extremely useful for optimizing emittance-compensating designs. A design that has been optimized can be scaled to any desired operating frequency. For S-band, the parameters associated with this optimum design are 1 nC of charge in a cylindrically uniform charge distribution of length 10 ps by radius 1 mm. Simulations indicate that using an appropriate rf design coupled with an emittance compensating solenoid, a normalized rms emittance of 10^{-6} m should be achievable simultaneously in all three planes at high energy (>100 MeV). Experimental confirmation of this conclusion is presently only approximate.

The results above have been obtained ignoring thermal emittance. Below, thermal emittance is defined as applied to metal and semiconductor photocathodes as well as thermionic cathodes.

2 Thermal emittance

The normalized rms transverse emittance, $\varepsilon_{n,rms}$, from a uniformly emitting thermionic cathode of radius r_c and operating temperature T is given [1] by

$$\varepsilon_{n,rms} = \beta\gamma\left(\left\langle x^2\right\rangle\left\langle x'^2\right\rangle\right)^{1/2} = \frac{\gamma r_c}{2}\sqrt{\frac{kT}{m_o c^2}}\,. \tag{1}$$

Thus the initial thermal emittance of a beam generated by a thermionic cathode can be determined by measuring the cathode temperature using a pyrometer.

The thermal emittance for beams extracted from photocathodes is generally taken to be the uncorrelated component of the beam emittance.

3 Photoemission from metals

Since kT~0.025 eV at room temperature, a cold emitter must have a low work function, Φ. The presence at the cathode of a strong electric field, E_c, will significantly lower the work function of photoemissive materials. Field emitters depend primarily on this factor. Photoemitters for practical electron beam sources are affected by three factors: Φ, T, and E_c, although use of elevated temperatures is rare.

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Photoemission from a metal involves first the absorption of a photon with $\hbar\omega > \Phi_e$, where $\Phi_e = \Phi - \Delta$. Here Δ is the lowering of the work function by E_c and is given [2] by $\Delta = e\sqrt{eE_c/4\pi\varepsilon_o}$. With normal-incidence illumination by a cylindrical laser pulse of radius r_c with uniform transverse and temporal distributions, the upper limit for the thermal emittance of the extracted electron bunch is given [3] by

$$\varepsilon_{n,rms}^{therm} = \frac{r_c}{2}\sqrt{\frac{2E_{kin}}{m_o c^2}}\frac{1}{\sqrt{3}}\sqrt{\frac{2+\cos^3\varphi_{\max} - 3\cos\varphi_{\max}}{2(1-\cos\varphi_{\max})}}, \quad (2)$$

where $E_{kin} = \varepsilon_F + \hbar\omega$ and ε_F is the Fermi energy. The maximum emission angle, ϕ_{max}, is given by

$$\varphi_{\max} = \arccos\left(\frac{\varepsilon_F + \Phi_e}{\varepsilon_F + \hbar\omega}\right)^{1/2}. \quad (3)$$

Using 4.6 and 7.0 eV for Φ and ε_F respectively for the case of a Cu cathode, and letting $\hbar\omega = 4.6$ eV (corresponding to λ=263 nm) and E_c=84 MV/m, we find $\varphi_{\max}$~10°. For a cathode of 1-mm radius, $\varepsilon_{n,rms}^{therm}$ is thus ~0.3×10^{-6} m. The thermal emittance adds quadratically to the residual correlated emittance at high energies, thus the total emittance predicted for an optimized S-band system using a metal cathode appears to be seriously limited by the thermal emittance.

Surface roughness will increase the local value of $\varphi_{\max}$ relative to the normal to the macrosurface. On the other hand, the effects of electron-electron scattering in the bulk as well as promotion from below the Fermi level, both of which would lower the thermal emittance, have been ignored. Any field enhancement due to the presence of surface contaminants or other factors has also been neglected. Such field enhancements for poorly prepared surfaces can be quite large, but it is noted that the field emission from which these enhancements are calculated (using a Fowler-Nordheim analysis) includes the gross area of the whole vacuum system subject to the high electric fields (the gun rf cavities in the case of an rf photoinjector system), while the electron beam is extracted from a much smaller area on the order of 1-mm radius for an S-band gun. In addition, field emission from Cu rf cavities can be greatly reduced by using special manufacturing techniques [4, 5].

Direct measurements of the thermal emittance of metals have not been made. However, since the quantum efficiency (QE) is proportional to $e^{-\Phi_e/kT_e}$, where T_e is the effective temperature of the excited electrons at emission, the change in the QE observed for a small change in Φ_e can be used to derive an experimental value of T_e [3]. In this manner a value of T_e=0.14 eV for a Cu cathode excited at 263 nm has been determined by changing the extraction phase to vary the Schottky effect [6]. From Eq. (1), a corresponding thermal emittance of 0.26×10^{-6} m per mm-radius is predicted for a transverse uniform pulse, which is consistent with the value derived earlier.

4 Photoemission from semiconductors

The principal energy-loss mechanism for electrons in a metal is electron-electron scattering. Near threshold, the primary electron can lose a significant fraction of its energy in a single scattering event, while the secondary electron may not gain enough energy to allow it to escape to vacuum. Thus the escape depth for metals is very short. By contrast, semiconductors lose energy primarily by electron-phonon scattering since electron-electron scattering is forbidden for excitation energies less than twice the band gap, E_{BG}. The photoemission process for negative electron affinity (NEA) semiconductors is illustrated in Fig. 1. First a photon with $\hbar\omega > E_{BG}$ is absorbed, promoting an electron from near the top of the valence band into the bottom of the conduction band. Second the excited electron loses energy by electron-phonon scattering as it diffuses to the surface. Since both the photon absorption length near threshold and the diffusion length for conduction band electrons are on the order of 1 μm while the thermalization length is ~10 nm, most of the conduction band electrons arriving at the surface have been thermalized. The third and final stage is discussed next.

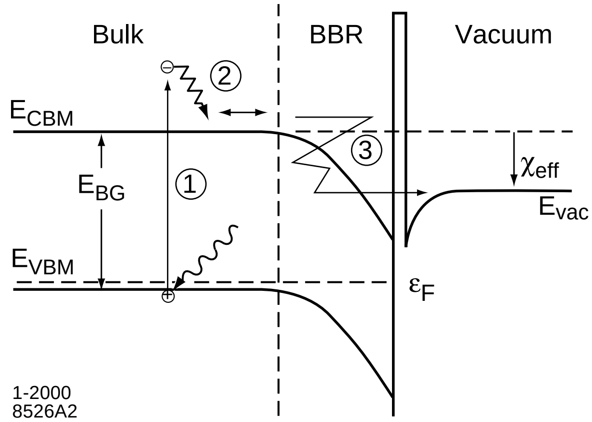

Fig. 1. Schematic energy diagram near the surface for p-doped GaAs illustrating the three-step emission process. E_{VBM}, E_{CBM} and E_{vac} are valence band maximum, conduction band minimum, and vacuum level energies respectively. E_{BG} is the band gap, ε_F the Fermi energy, and χ_{eff} the effective electron affinity.

The electron affinity, χ, is defined as the difference in energy between vacuum and the conduction band minimum (CBM) at the surface. The χ of many materials including most semiconductors can be significantly reduced by coating the surface with a monolayer or so of an alkali metal such as Cs. Adding a small amount of an oxide facilitates this process. For III-V semiconductors, this will lower the vacuum level to about the CBM in bulk. In addition, if the semiconductor is p-doped, negative band bending is exhibited at the surface, so that the vacuum level at the surface is actually below the CBM in bulk, resulting in an NEA emitter. Under these conditions an effective electron affinity, χ_{eff}, defined as the energy difference between vacuum and the CBM in the bulk, is used as shown in Fig. 1. For an NEA cathode, χ_{eff} is negative, whereas χ itself remains positive. The band bending results from the positive charge associated with the surface dipole layer. Since for high doping density (~10^{19} cm^{-3}) the width of the band bending region (BBR) is only about 10 nm, extremely high electric fields are present that can greatly increase the kinetic energy of a transiting electron. Although the mean free path (MFP) for electrons is greater than the BBR width, most of the excited electrons approaching the surface are reflected by a thin interfacial barrier, as indicated in the figure, or trapped in surface states. However, energy-wise the reflected electrons are confined to the BBR where they tend to heat up before some of them manage to tunnel through the surface barrier to vacuum while the remainder eventually recombine with holes [7].

A measurement of the mean energy parallel to the surface, $\varepsilon_{//} = \hbar k^2 / 2m_e^*$, as a function of the mean perpendicular energy, $\varepsilon_{\perp}$, for an NEA GaAs photocathode is shown in Fig. 2. The measurement was performed by the Heidelberg group [8] using a novel technique that eliminates the effect of space charge on the measured parallel energy. It is seen that of the electrons escaping to vacuum, only the “hot” electrons (electrons promoted near the surface) and the thermalized electrons from the bulk that have not experienced significant energy loss in the BBR retain their low temperature [9].

The experimental data discussed above suggest that to minimize the thermal emittance using a semiconductor photocathode, it should be operated with χ_{eff}~0. The effective temperature of the emitted electrons would then be ~0.025 eV compared to ~0.14 eV for the Cu example discussed earlier, resulting in more than a factor of 2 reduction in the thermal emittance per mm-radius. Cooling the cathode to ~100 K would reduce the thermal emittance another factor of $\sqrt{3}$. Operating at χ_{eff}~0 will reduce the QE by about an order of magnitude, or to a level of ~1% (~0.1%) for thick (thin) GaAs, which is still high considering that the excitation light, at threshold, is in the near-IR regime.

5 RF gun issues

There are four major issues associated with operating an rf gun using a III-V semiconductor as the photocathode: time response, vacuum, dark current, and cathode charge limit

The time-response issue has been largely resolved. For an epilayer 150-nm thick, the maximum emitted pulse length will be on the order of 10 ps for low charge if promoted by a short (<1 ps) laser pulse [10].

Faster response times are expected for a positive electron affinity (PEA) cathode—defined as $\chi_{eff}>0$—in which most of the emitted electrons originate within 10 nm of the surface. Clearly the time response favors a lower frequency rf gun: S-band would be marginal, L-band should be better.

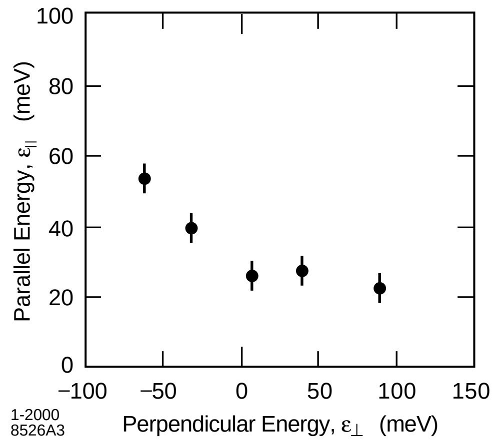

Fig. 2. Mean energy parallel to the surface, $\varepsilon_{//}$, as a function of the mean emission energy perpendicular to the surface, $\varepsilon_{\perp}$, with respect to the conduction band minimum, E_{CBM}. Thermalized conduction band electrons have a kinetic energy of ~25 meV.

Successful dc-biased polarized guns are carefully constructed using mostly stainless-steel, are vigorously pumped with both ion and NEG pumps, and operate with a vacuum of 10^{-11} Torr (dominated by H_2) or better [11]. By contrast, rf guns are constructed of Cu, and the best operating pressures are about 10^{-9} Torr. A significant amount of materials and general research has been done on how to construct an S-band Cu rf cavity to minimize rf breakdown and dark current while operating at high fields [5], but to date these techniques have not been applied to a cavity designed for GaAs photocathodes. Even applying these techniques, it will probably be necessary to find some sort of protective coating for the activated GaAs crystal before one can hope to achieve the lifetimes (at least hundreds of hours) needed for a practical rf gun . An effort to find an analog to the CsBr coating used with K-Cs-Sb [12] and Cs_2Te [13] photocathodes that can be used with GaAs has been proposed by the SLAC-St. Petersburg group [14]. Some improvement in the robustness of a GaAs cathode may also be associated with variations in the standard activated technique [15].

For a dc-biased polarized gun, dark currents on the order of 50 nA or more have been found to decrease the lifetime regardless of vacuum. The dark current problem can normally be eliminated by high voltage (HV) processing the gun before inserting the photocathode (using a load lock system) or by pulsing the HV [16]. The gradients are so much higher in rf guns (on the order of two orders of magnitude) that in a typical gun the dark current dominates over the photocurrent, resulting typically in a significant pressure rise during rf operation of a factor of 2 (or more) higher than the quiescent pressure. By contrast, for a properly designed dc-biased gun, the vacuum remains constant when the HV is switched on or off. However, if the duty cycle for the rf is low, the average dark current may still be well below the maximum value derived from dc gun studies. In fact, in one study with an unactivated 12-mm diameter GaAs crystal (coated with Cs) in an S-band gun, an upper limit of the dark current was estimated to be 60 pC per μs of rf at 6 MV/m [17], which corresponds to an average current of ~20 nA for a 2-μs rf pulse at 180 Hz. On the other hand, since the field emitted electrons in an rf gun are much more energetic than for a dc biased gun, the maximum dark current that can be tolerated in an rf gun is yet to be determined. Although dark current from the Cu structure can probably be eliminated if enough care is taken, there is also the dark current and rf breakdown problem of the rf plug which has not been fully solved for gradients above ~100 MV/m.

A properly prepared semiconductor crystal surface is flat and unlikely to have any significant faults on the micron scale. Thus the Fowler-Nordheim β factor for the photocathode itself should be very low. In addition, there is actually no fundamental reason that an NEA semiconductor should field emit since there are essentially no free conduction band electrons when optical excitation is absent unless, possibly, if 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 dc field of ~50 MV/m, although rapid accumulation of free electrons would require significantly higher fields. However, for high frequency fields (>100 Hz), the recombination-generation rates for the minority carriers (in this case electrons) cannot keep up with the field variations, and so an inversion layer doesn't actually form [18].

A limitation on the current density that could be generated from a GaAs photocathode in a dc-biased gun using a short excitation pulse was discovered with the turn on of the SLC polarized electron source in 1991 [19]. As the laser energy at threshold was increased above a certain value, the extracted current was found to saturate well before reaching the space charge limit of the gun. Under the conditions of the SLC source (2-ns pulse with radius of 0.7-1 cm), the value of the current density at which saturation began increased with both cathode QE and bias. Due to the Schottky effect, the QE is expected to increase with cathode bias, although the effect is most pronounced at low QE and may vary with pulse length as well [20]. It is also clear that the effect is less limiting for excitation well above threshold, but for a low emittance source as for a polarized source the excitation energy must be at or near threshold χ_{eff} ~0, as discussed earlier.

Since for an rf gun the field at the cathode during excitation is much higher than for a dc-biased gun, one might expect the cathode charge limit to be less of a problem. However, the charge one is trying to extract is about the same, while the pulse length and beam radius (10 ps and 1 mm for an S-band gun) are much smaller. Fortunately there has been significant progress in understanding and mitigating the cathode charge-limit effect. The essence of the understanding is that this charge limit is purely a surface effect that arises when the conduction-band electrons are trapped at the surface—neutralizing the positive surface charge—at a rate exceeding their discharge, where the discharge mechanism for a highly p-doped cathode is predominately tunneling of holes through the band bending (i.e., the depletion) region [21]. It has been shown that by increasing the concentration of acceptors (dopant density) at the surface to the level of 10^{20} cm^{-3}, as well as by increasing the gap between the effective CBM and valence band maximum (VBM), will significantly reduce (or possibly eliminate) the cathode charge limit effect [22], presumably because of the increased tunneling rate.

6 Gun structure

Given the relatively daunting environment in which an activated GaAs cathode must live in order to be used as a photocathode for an rf gun, an extraordinary amount of care must go into the design of the gun structure itself. In order to minimize the dark current, it appears the rf fields should be kept well below 100 MV/m. For an emittance-optimized gun, this can be done with either a low-frequency (L-band or lower) gun, or with an integrated-structure S-band gun [23].

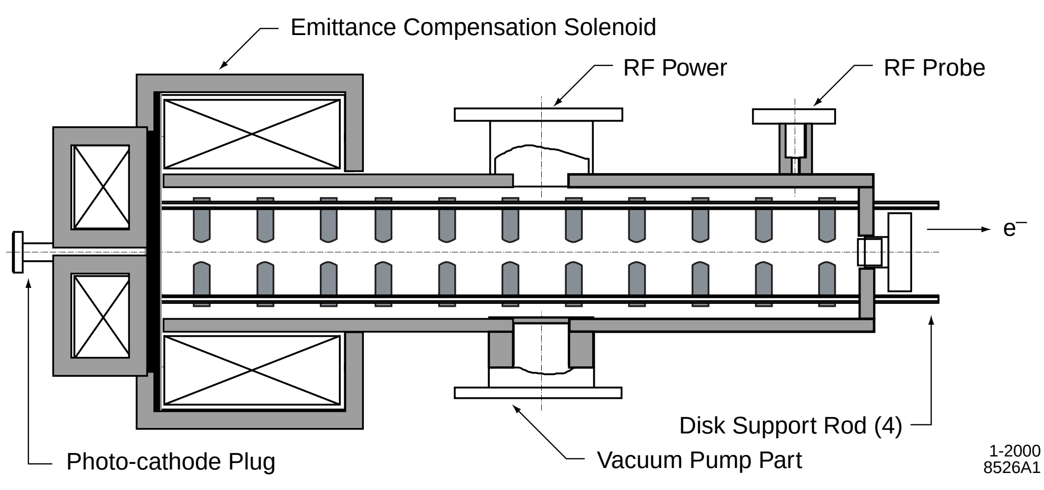

Fig. 3. Cross-section of the UCLA/Duly 1/2+10+1/2 cell plane-wave-transformer (PWT) rf gun.

For several reasons the S-band plane-wave-transformer (PWT) gun, shown in Fig. 3, developed by UCLA in collaboration with Duly Research [24], is an inviting choice for the design for a low emittance rf gun using III-V semiconductor photocathodes, especially if one desires to operate at S-band. First the emittance can be optimized with a peak field of ~60 MV/m, about half the field needed for the BNL/SLAC/UCLA 1.6-cell S-band gun. Second, the open rf structure allows for better pumping of the photocathode area. In addition the outer structure of the gun could be made from stainless steel rather than Cu with only slight modification of the dimensions and for these purposes a negligible drop in performance [25]. One could presumably turn the inner walls of this outer structure into a giant vacuum pump by coating them with an alloy of Ti and Zr following the suggestion in reference [26]. If such a PWT gun were constructed using the techniques discussed in reference [5], assembled and operated under the exceedingly meticulous conditions discussed therein, then one might expect the high QE and long lifetimes of at least hundreds of hours needed for a practical electron source.

7 Conclusions

It has been shown that the thermal emittance of an rf gun can be significantly reduced by using a III-V semiconductor photocathode. This may prove useful if the very low emittances predicted for certain photoinjector designs are to be realized in practice. The known problems for actually operating these cathodes in rf guns are expected to be manageable if known techniques are carefully applied. Finally, an appealing rf gun structure based on the PWT design and operating with these cathodes is discussed.

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