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Possible Photocathode for the RF Gun

Some of the goals for the photocathode performance are

- Cathode radius $\sim 20\,\mu$m;
- Transverse energy $\sim$ 0.1 eV. (Together these imply an emittance of $r\theta \sim 1.3 \times 10^{-10}$ m-rad at 50-MeV beam energy.)
- $\sim 10^5$ electrons per pulse;
- Pulse length of a few picoseconds, so no further bunching is needed, and the final beam-energy spread may be reduced;
- The option to have many more electrons distributed over a klystron pulse of $\sim 1\,\mu$sec duration.

These goals are ambitious. In particular, the shortest pulse off a photocathode measured to date is about 17 psec fwhm (C.C. Phillips *et al.*, J. Phys. D **17**, 1713 (1984)). Furthermore, a pulse of 10^5 electrons extracted from a 20 μm spot by a field of 10^7 Volts/meter is right at the space-charge limit, so there is danger of pulse broadening in the gun even if a picosecond pulse is emitted from the photocathode. Another way of dramatizing our goals is that the peak current density would be 10^5 Amps/cm^2 for a pulse length of 1 psec.

Given the choice of a Nd:YAG laser to drive the photocathode some additional constraints arise:

- To be able to fire the photocathode more than once a second, we should use light from the mode-locked laser rather than the low-rate amplifier;
- The readily available photon energies are 1.17, 2.34 and 4.68 eV, corresponding to the fundamental, doubled, and quadrupled frequencies;

- The Spectra Physics mode-locked laser will operate at 81.6 MHz, and (with frequency doubling and pulse compression) can deliver a train of 2.34-eV pulses about 3 psec wide at an average power of 0.5 Watt. Each pulse then contains about 1.6×10^{10} photons;

- Thus we could use a cathode of quantum efficiency as low as 10^{-5}. If we wish to multiplex the laser pulse to achieve a rate of 571 MHz or 2856 MHz we would need a quantum efficiency of 10^{-3}-10^{-4}.

There are 3 types of photocathodes we might use, in order of increasing quantum efficiency and complexity of preparation;

- A pure metal such as CS ($\phi = 2.15$ eV) or W ($\phi = 4.55$ eV);

- A semiconductor such as Cs_3Sb or Rb_3Sb. (If it were required to operate at 4.68 eV, Cs_2Te or Rb_2Te might do.);

- A Negative-Electron-Affinity semiconductor such as GaAs(Cs,O) or GaAsP(Cs,O).

I believe a Cs_3Sb photocathode operated with 2.34-eV photons is the likely choice. (For possibly different reasons this is used for the Los Alamos RF gun.) With this we might achieve

- Quantum efficiency of $\sim 3\%$ for 2.34 eV photons (and hence the option to produce pulses of 10^8 electrons with a larger area cathode, for a total charge of about 10^{10} electrons in a μsec);

- psec time response as the cathode is only ~ 300 Å thick;

- Transverse energies up to 0.3 eV, with a low-level tail up to 0.8 eV;

- Simpler activation procedure than for GaAs cathodes, but the Cs_3Sb film must be deposited *in situ* and in vacuum below 10^{-9} Torr;

- Cathode illuminated from behind through a sapphire window.

The problem with a pure metal is the low quantum efficiency (due to high relection of

the light, and severe inelastic scattering of the photoelectron while still in the metal). To obtain a narrow electron-energy spread the photon energy must be only 0.1-0.2 eV above the work function. In this case the quantum efficiency is only 10^{-6}-10^{-7}. While this is not a problem in principle, only amplified laser pulses would suffice. On the positive side, surface preparation and vacuum requirements are modest. Also since the electrons can only escape without energy loss when the are produced very near the surface, a picosecond response time could be achieved.

Negative-electron affinity cathodes achieve their large quantum efficiency by a trick which necessarily implies a slower time response. Photoelectrons can be promoted well into the conduction band by the incident light, and subsequently thermalize unitl they lie at the bottom of the conduction band. Here they can travel several microns without great loss. These thermal electrons would not have enough energy to escape over the work function, but the Cs + O surface treatment miraculously reduces the work function to less than the band-gap energy, and so any electron in the conduction band can escape. While quantum efficiencies of 20% are achieved, the thermal electrons drift (diffuse) for much longer than a picosecond before emerging. The 17-psec pulse mentioned above was obtained with this kind of cathode, but with a thickness of only 500 Å, which limited the quantum efficiency to 10^{-3}. Furthermore, to get narrow a electron-energy distribution, the laser energy had to be about 1.6 eV, just above the band gap. Thus this exotic material had essentially been restored to pure-metallic behavior when a short pulse was desired!

Cesium-Antimony.

The standard compilation of lore on Cs_3Sb is the book *Photoemissive Materials*, by A.H. Sommer (Wiley, 1968).

A thin layer ($\sim$ 300 Å) of Cs_3Sb can achieve a quantum efficiency of about 3% for 2.34-eV photons because of two notable features. As shown in Fig. 26 (from Sommer) the photo-absorption length is about 500 Å at 2.34 eV, so only a thin layer need be used. Also, as sketched in Fig. 4, the work function is 2.05 eV while the band-gap energy is 1.6 eV. Taking into account momentum as well as energy conservation, a 2.34-eV photoelectron cannot promote another electron across the band gap, so there is little energy loss as the photoelectron travels to the surface. Energy loss does occur

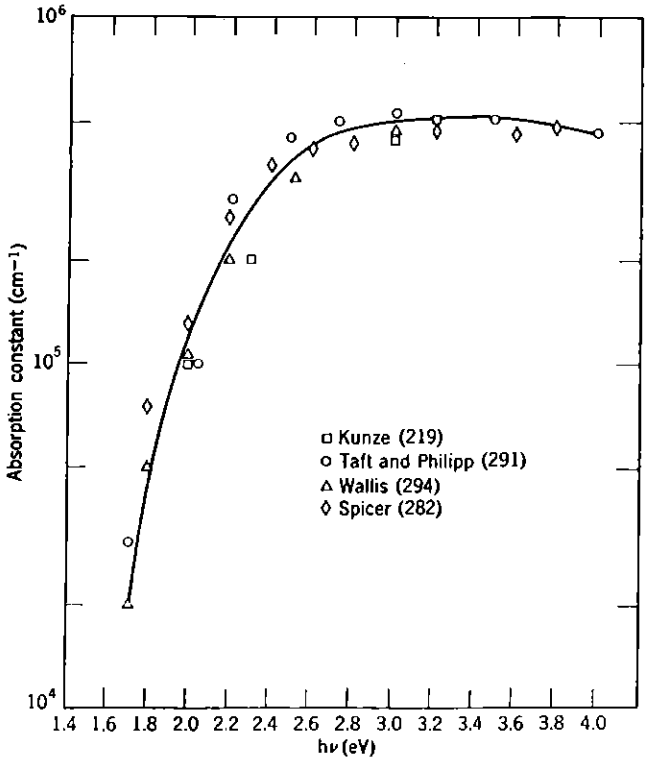

Figure 26. Absorption constant of Cs_3Sb. Comparison of results by Wallis [393] Spicer [347], Taft and Philipp [372], and Kunze [193].

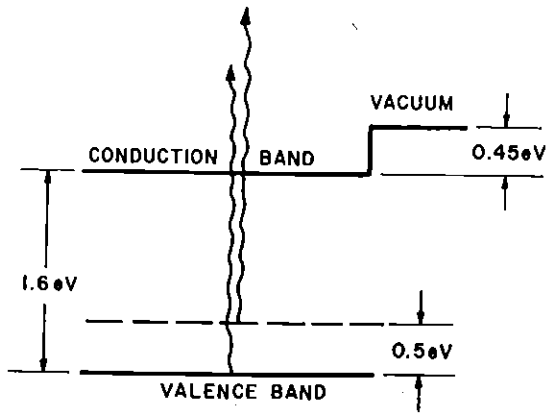

FIG. 4. Energy diagram of cesium antimonide. It shows two electrons from different energy level excited to conduction band by absorbing same energy photon.

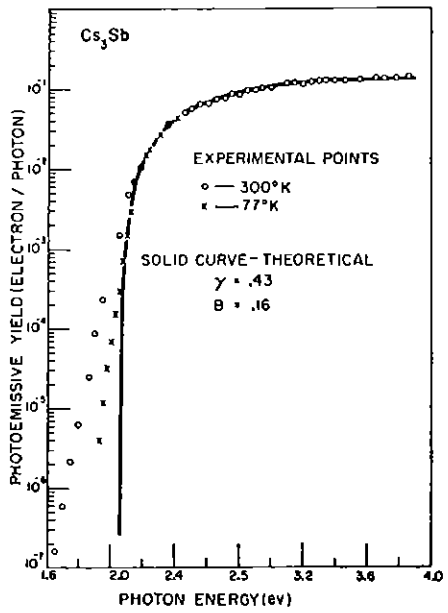

FIG. 8. Photoemission from Cs_3Sb. The points are experimental and the solid curve is theoretical. As with the other materials which showed p-type behavior, cooling decreases the photoemission in the threshold region. The room temperature and liquid N_2 temperature points have been fitted vertically. An E_0+E_A value of 2.05 ev is obtained.

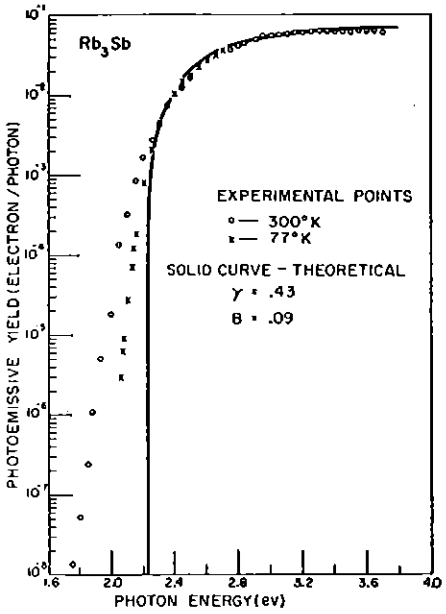

FIG. 9. Photoemission from Rb_3Sb. The points are experimental and the solid curve is theoretical. Room temperature and liquid N_2 temperature points have been fitted vertically. An E_0+E_A value of 2.20 ev is obtained.

due to electron-phonon collisions, and the resulting escape length is apparently about 250 Å. Hence a large fraction of the photoelectrons will escape, as summarized in Fig. 8 (from W.E. Spicer, Phys. Rev. **112**, 114 (1958)).

Other bi-alkali photocathodes have even lower work functions and are more suitable for phototubes. As we desire a narrow electron-energy distribution the work function should be only slightly less than 2.34 eV. If Cs_3Sb produces too wide an energy spread, there remains the option of a Rb_3Sb photocathode (Fig. 9) where the band-gap energy of 2.2 eV leads to a quantum efficiency of 0.7%, perhaps 1/5 as large as that for Cs_3Sb.

An annoying feature of Cs_3Sb is the presence of defects leading to acceptor levels lying up to 0.5 eV above the top of the valence band. Thus there is actually some quantum efficiency for photon energies as low as 1.55 eV, as seen in Fig. 8. Cooling the photocathode reduces the population of the defect levels. When using a 2.34-eV photon source, electrons from the valence band can emerge with a maximum of 0.29 eV, but the acceptor levels add a low-level tail to the spectrum, extending up to 0.79 eV.

A recent study of the electron-energy distribution from a Cs_3Sb photocathode was reported by C. Lee, J. Appl. Phys. **54**, 4578 (1983) (he was an industrial consultant to the Los Alamos RF gun project). However he shows the full energy distribution only for a photon energy of 1.96 eV, for which all photelectrons are from the defect levels, so the quantum efficiency is low and the tail to high electron energy is quite pronounced. If we really want to know this kind of detail we will probably have to measure it ourselves.

Discussions of the Cs_3Sb surface preparation written after the book of Sommer include

G.K. Bhide *et al.*, J. Phys. D **4**, 568 (1971);

C. Lee and P.E. Oetinnger, Rev. Sci. Instr. **56**, 560 (1985).

The latter paper reports a cathode lifetime of 50 hours at a current density of 3 Amps/cm^2. Assuming the lifetime to be proportional to the total charge (per cm^2)

delivered, we might expect a lifetime of 0.5 sec of beam at 10^5 Amps/cm^2, or $> 10^{11}$ shots. Given this large value, in practice we may expect contamination of the vacuum to limit the lifetime rather than actual use of the cathode.

The photocathode will be operated in an RF field of 10^7 Volts/m. This field may reduce the work function of the surface, and lead to a background from field emission.