Simple photoelectronic source for swarm experiments in high-density gases

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A simple photocathode for electron injection into high-density gas is described. Relatively large electronic current pulses have been obtained by using a commerical low-power xenon flash lamp. The photocathode efficiency has been studied as a function of the metal film thickness. The device has been used in swarm experiments at pressures up to 10 MPa in the temperature range 40–300 K.

INTRODUCTION

Photocathodes are frequently used as electronic sources in swarm experiments.[1–4] In such experiments the transport parameters of electrons moving through a gas under the influence of an electric field are measured, and useful information is derived on the various electron cross sections.

In the most common design the photocathode is a bulk electrode irradiated at an angle by a light beam that enters the cell through a side window. In such a configuration the large amount of light reflected by the cathode may give unwanted photoemission inside the drift cell. In fact, when accurate time-of-flight measurements are performed, the electron source geometry must be well defined in order to avoid uncertainty on the effective drift distance. In the "pulsed Townsend" technique with parallel-plate geometry, for instance, all the electrons have to be emitted from the cathode surface and, therefore, the light impinging on other metal surfaces (e.g., guard rings or field-shaping electrodes) has to be minimized. Moreover, in certain gases the light beam passing through the sample may also produce an undesired chemical reaction.

To prevent a large amount of light from entering the sample cell, a different design was first suggested by Moruzzi[5] who obtained the photocathode by evaporating a thin metal film onto the inner surface of the optical window and providing an electrical spring contact with the film. With a proper choice of the film thickness, the transmitted light intensity could be made much smaller than the reflected one, while a significant fraction of the electrons released within the film could still enter the sample cell. Here we give a practical criterion for the choice of the best film thickness and we suggest a very simple design of a pulsed electron source that is suitable for swarm experiments a high pressure and at low temperature.

I. A SIMPLE MODEL

The behavior of a transmission photocathode can be qualitatively predicted through simple calculations.[6]

Let us assume a monochromatic light beam perpendicular to the Y-Z plane of the metal film, with a photon energy $h\nu$ larger than the threshold energy. Let $I(0)$ be the light intensity entering the metal film at $x=0$. The light beam intensity at a given depth x inside the film is then given by

$$I(x) = I(0)\exp(-\gamma_1 x)\,, \tag{1}$$

where γ_1 is the light absorption coefficient.

The number of electrons per unit length $dN(x)$, which acquire an excess energy $h\nu$ and a positive velocity component along the X direction is proportional to the light intensity and is given by

$$dN(x) = \alpha I(x)\,dx\,, \tag{2}$$

where α is an appropriate coefficient which describes the efficiency of the process.

The excited electrons inside the metal have a finite escape length $\lambda_2 = \gamma_2^{-1}$, so that only a fraction $\exp[-\gamma_2(s-x)]$ of the electrons released at x will reach the film-free surface at $x=s$. The total number of excited electrons arriving at $x=s$ is therefore

$$N(s) = \int_0^s \exp[-\gamma_2(s-x)]\,dN(x)\,. \tag{3}$$

Only a fraction $N_e(s) = \beta N(s)$ will escape through the surface barrier and will be injected into the drift space.

The "escape coefficient" β depends on the metal–gas work function, on the temperature, on the light wavelength and on the X component of the applied electric field close to the film surface.

The effective number $N_e(s)$ of the emitted electrons is therefore given by

$$N_e(s) = \frac{I(0)\alpha\beta}{\gamma_2-\gamma_1}[\exp(-\gamma_1 s) - \exp(-\gamma_2 s)]\,. \tag{4}$$

On the other hand, the light transmitted by the metal film will also produce photoelectrons by irradiating the collector surface. With a reversed electric field the number $N_c(s)$ of the electrons photoemitted by the collector is expected to be

$$N_c(s) = \frac{I(0)\alpha\beta(1-r)}{\gamma_2+\gamma_1}\exp(-\gamma_1 s)\,, \tag{5}$$

where r is the reflectivity of the collector surface.

From Eq. (4) we expect a maximum in the forward emission N_e at a thickness $s_m = \ln(\gamma_2/\gamma_1)/(\gamma_2-\gamma_1)$.

The electrons we are dealing with have energies of few eV and therefore their escape length λ_2 is quite short: $\lambda_2 \approx 10$ Å.[7,8] The light absorption coefficient γ_1 is of the order of 0.01 Å^{-1},[9] so that we get $\gamma_1/\gamma_2 \approx 0.1$ and $s_m \approx 25$ Å. For $s > s_m$, Eq. (4) reduces to

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$$N_e(s) \approx \frac{I(0)\alpha\beta}{\gamma_2 - \gamma_1} \exp(-\gamma_1 s), \quad (6)$$

and, therefore, a plot of the photocathode emission at various thicknesses yields the light extinction coefficient of the given metal.

The criterion of strongest emission should suggest s_m as the best choice for the film thickness. Such a film, however, can be hardly obtained with a sufficient uniformity and even with electrical continuity. Therefore, a minimum 50-Å thickness seems to be a good "rule of thumb." By using a thicker film the decreased electron yield would require larger light input and, therefore, the same emission should be obtained by dissipating more heat inside the film.

II. CONSTRUCTION DETAILS

An exploded view of the device is given in Fig. 1. The photocathode substrate S is a uv-grade fused silica disk (Spectrosil B) 25 mm in diameter and 1 mm thick. One face of the substrate is metallized by a two-step evaporation: (i) The central region of the window with a diameter of about 10 mm is first masked and a thick gold layer ($\approx$2000 Å) is deposited onto the outer ring to obtain a safe electrical contact; (ii) after the mask is removed, the thin active metal film is deposited to the desired thickness onto the whole area.

Two metals have been tested as electron emitters: Au and Pd. The evaporations were performed in a standard high vacuum deposition system equipped with a 10-kW electron gun (Varian Model 3117). The substrates were located 15 cm above the source. Au was evaporated from a Joule-heated tungsten crucible; Pd was evaporated with the aid of the e-gun from a water-cooled copper crucible. The deposition rates of the films were $\approx$40 Å/min for Au and $\approx$9 Å/min for Pd, with a residual gas pressure of $\approx 10^{-6}$ Torr and at ambient temperature. The film thickness was measured within $\pm$10% by a standard quartz oscillator (Kronos model QM301). The choice of a large crucible–to–substrate distance and of a very low deposition rate was made in order to obtain a good film uniformity.

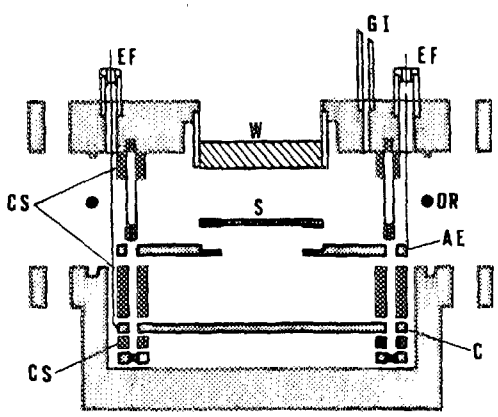

FIG. 1. Exploded view of the low-temperature/high-pressure photocathode cell. EF: electrical feedthrough; AE: annular electrode; S: photoemitter substrate; C: collector; CS: ceramic spacers; W: optical window; GI: gas inlet; OR: Indium O-ring.

After the evaporation, the disk was gently tightened against the optical window W by means of the annular electrode AE. The emitter and the collector C are kept apart by cylindrical ceramic spacers CS. Both AE and C are brass made and Au (or Pd-) coated to avoid contact potential effects. The high-pressure optical window W is also made by UV-grade fused silica. It is 5 mm thick and it is sealed to a thin-walled Invar collar[10] by means of a suitable epoxy resin (Stycast 2850FT, manufactured by Emerson & Cumings). This invar collar, previously soft soldered to the solid brass flange, provides a simple and reliable flange-to-window seal, which is leak tight after several thermal cycles between room and cryogenic temperature ($18 \leqslant T \leqslant 300$ K) and with inner pressures up to 10 MPa.

The use of Invar is unavoidable with a window of fused silica (thermal expansion coefficient $\approx 5 \times 10^{-7}$ K^{-1}), but we also successfully used a stainless-steel collar with a sapphire window. This alternative solution is, however, less satisfactory because of the lower light transmission coefficient of sapphire in the VUV range.

As UV light source we used a pulsed xenon lamp (EG&G Model 108FXAU), whose total radiant output is $\approx 600\,\mu$J/sr, with a pulse width $\Delta t \approx 4\,\mu$s. The light output, averaged over the useful wavelength interval ($\approx$2000–2500 Å), is of the order of $\approx 60\,\mu$J/sr. In our experimental arrangement the effective number of photons per pulse reaching the active film area is $\approx 10^{11}$.

III. DEVICE PERFORMANCE

Several Au and Pd photoemitters with different film thicknesses have been tested under vacuum at room temperature.

The electronic current pulse $i(t)$ is integrated by the parasitic capacity C_p in parallel to the input capacity C_i of a transient recorder (Hitachi Model VC6041). The total integration capacity $C_T = C_P + C_i$ was calculated from the measured discharge time constant RC_T, where $R(=1\,\text{M}\Omega)$ is the input resistance of the transient recorder. The number of the collected electrons is calculated as $N_e = C_T V^-/e$, where

$$V^- = (1/C_T) \int i(t)\, dt$$

is the amplitude of the measured voltage signal with the photocathode negatively biased with respect to the collector and e is the electron charge. Similarly, the number of electron emitted by the collector is $N_c = C_T V^+/e$, where V^+ is the measured voltage when the photocathode is positively biased.

A typical record of the measured signals is shown in Fig. 2. The light pulse shape is shown in Fig. 3. Here, in order to reduce the effective time constant RC, a smaller input resistance has been used. The signal is then amplified by a fast preamplifier, placed close to the collector.

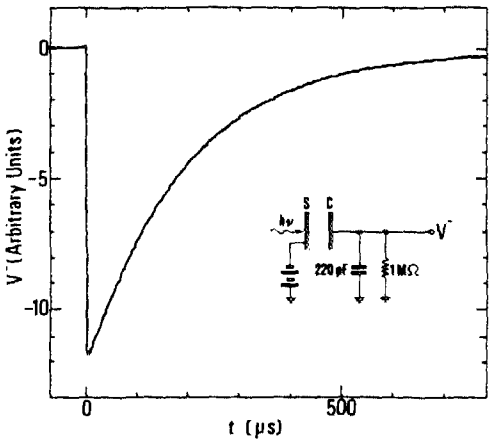

FIG. 2. Collector voltage signal V^- under vacuum at room temperature without preamplifier: the time constant is $\tau \approx 0.2$ ms. S: photocathode; C: collector.

Results obtained with an applied electric field $E = \pm 64$ V for Au and Pd are reported in Fig. 4. At such high electric field values the electron emission is field independent, but it does depend on the film thickness, on the film age and on the residual gas pressure.

The data reported in Fig. 4 have been taken with a residual gas pressure of $\approx 10^{-4}$ Torr and with samples aged for about six months in moist air at room temperature. From the slopes of the curves, we can extract the light extinction coefficient in Au and in Pd: $\gamma_1 \approx 0.008$ Å^{-1} for Au and $\gamma_2 \approx 0.011$ Å^{-1} for Pd, in good agreement with the commonly accepted values.[9]

The effect of the emitter aging is depicted in Fig. 5 for Au, where the electron yield is reported as a function of the film thickness at different times. The efficiency decrease with time is probably due to oxygen and moisture absorption onto the cathode surface.[5] A partial recovery of the photocathode performances may be obtained in fact by baking for a long while under high vacuum.

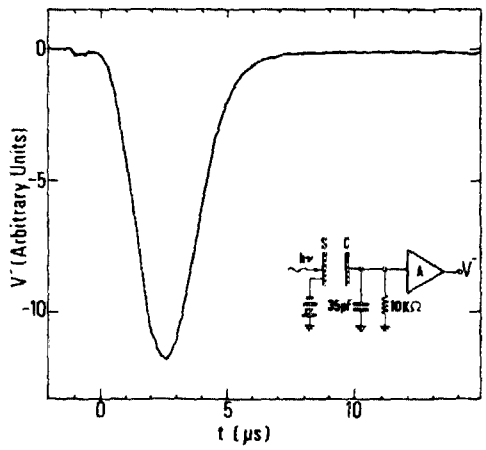

FIG. 3. Collector voltage signal V^- under vacuum at room temperature with preamplifier: here the fast preamplifier A (Gain = 100) and the small load resistance give a time constant ($\tau \approx 0.3\,\mu$s) low enough to fairly reproduce the light pulse shape. S: photocathode; C: collector.

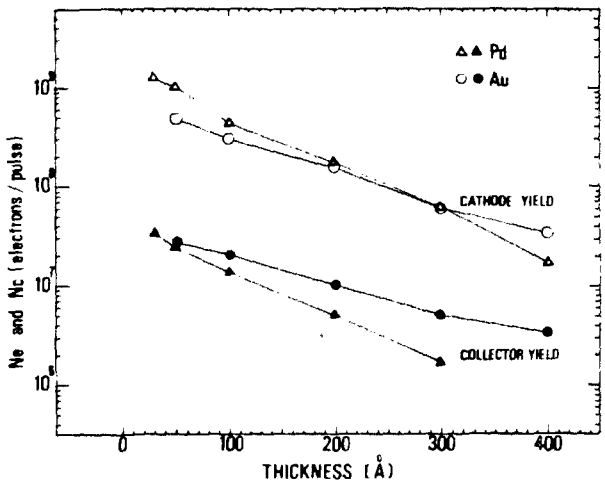

FIG. 4. Photocathode electron yield as a function of the metal film thickness. Open symbols refer to N_c (i.e., metal film negatively biased with respect to the collector); full symbols refer to N_c (metal film positive with respect to the collector).

A similar plot is obtained for Pd, where the aging rate turns out to be higher. In fact, the Pd/Au efficiency ratio is of the order of 10 for freshly prepared samples, but it drops very rapidly down to 1 (or less) after aging. In spite of its higher electron yield, palladium is less recommended than gold due to the faster film degradation and the more complicated evaporation techniques.

Figure 6 shows a typical record of the signal obtained in electron time-of-flight measurements in neon gas with a gold emitter 50 Å thick, a drift distance of 1 cm, an applied electric field $E = 30$ V/cm, and a gas pressure $P = 1.8$ MPa at $T = 48$ K.

The output voltage signal $V^-(t)$ is due to the charge $Q(t)$ induced on the collector by the drifting electrons. $Q(t)$ is actually detected as a voltage drop across the effective integrating capacity C_T in parallel to the amplifier input:

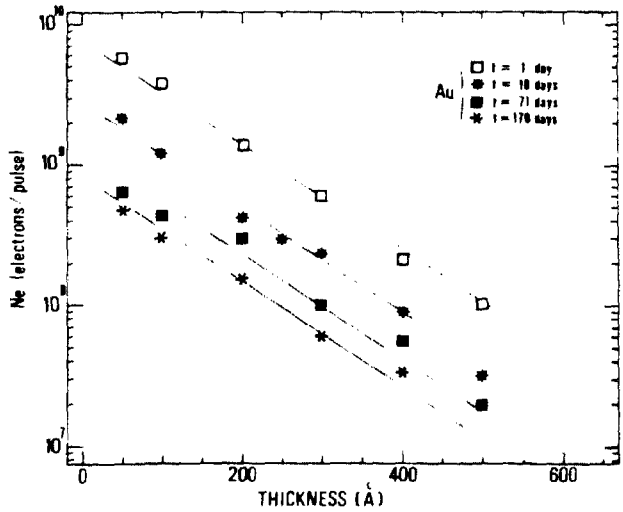

FIG. 5. Electron yield as a function of the film thickness at different times for Au photocathodes.

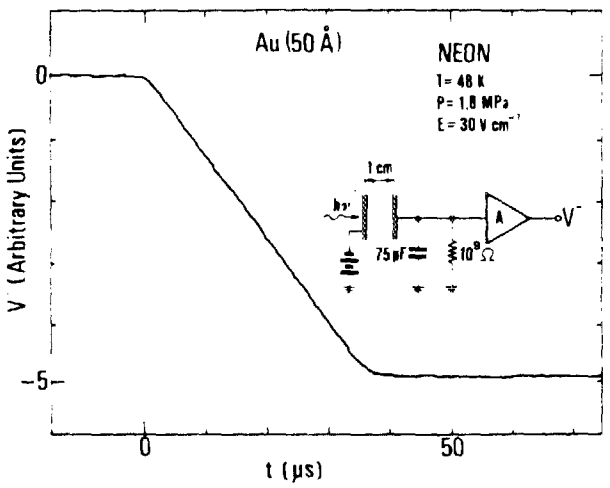

FIG. 6. Collector voltage signal V^- in neon gas. Here the integration time constant is 75 ms, obtained with a small effective capacity and a high load resistance in order to improve the signal-to-noise ratio.

$V^-(t) = Q(t)$. Alternatively, $Q(t)$ may be seen as the integral of the current $i(t) = -en(t)A(t)v(t)$, where $-en(t)$ is the charge density, $A(t)$ is the effective swarm cross section, and $v(t)$ is the drift velocity.

In the case shown in Fig. 6, diffusion and attachment processes are negligible, so that both $n(t)$ and $A(t)$ are constant. Moreover, owing to the scattering with the gas atoms, the electrons drift with constant speed, and therefore, $Q(t) = (-enAv)\cdot t$ for $0 \leqslant t \leqslant \tau = d/v$, where τ is the time of flight and d is the electrode separation (= drift distance). For a very short injection pulse ($\Delta t \ll \tau$), the signal should appear as a straight line starting at $t = 0$ and ending at $t = \tau$, and for $\tau < t \ll RC_T$, $V(t)$ is practically constant.

When the pulse width is not negligible, however, the starting and ending edges are smeared out as in Fig. 6 ($\Delta t \approx 4$ μs). Beside the finite pulse width, other experimental parameters must also be considered in order to achieve an accurate measurement of τ. The collected signal shape, in fact, may strongly deviate from the linear behavior owing to electron attachment to molecular impurities, diffusion processes, space-charge effects, and finite size of the electrodes. A detailed analysis of such effects is beyond the purposes of the present work, and it can be found elsewhere.[11]

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