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PHOTOELECTRIC EFFECT INDUCED BY HIGH-INTENSITY LASER LIGHT BEAM FROM QUARTZ AND BOROSILICATE GLASS*

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ABSTRACT

Using a high-intensity light beam from a ruby laser, the number of photoelectrons from quartz and the number of photoelectrons for borosilicate glass were measured as a function of the laser output power. The number of electrons is an exponential function of the field in the light beam. The delay between the maximum of the electron current and maximum intensity of the light pulse decreases with increasing output power. Previous low-intensity experiments on photoelectron emission from borosilicate glass have shown that the photon energy must exceed 4.9 electron volts, but in the present experiments electron emission was observed with 1.78 electron volt photons. Thus the present experiments cannot be explained purely on the basis of the photoelectric effect. However, by using the theory of thermal breakdown in a dielectric surface the observed electron current as function of the light beam power can be explained. The yield of electrons from borosilicate glass exceeds the yield from quartz at the same photon intensities.

The experimental investigation of the photoelectric quantum efficiency from borosilicate glass was reported by V. K. Rohatgi.[1] In this experiment the glass was illuminated by ultraviolet light, and the photoelectric current was measured as a function of the wavelength of the incident light. In this low-intensity experiment photons above 3300 Å (or below 4.25 electron volts) did not contribute to the photoelectric current in any fashion, and the photoelectric quantum efficiency decreased from 10^{-3} at 1250 Å to 10^{-4} at the wavelength of 2300 Å. The photoelectric current was apparently caused by the photoelectric ionization of some 10^{13} Na atoms per cm^2 in a glass surface layer of some 10 Å thick. The energy of the photons used in this experiment is just below the ionization potential, 5.1 volts of isolated Na atoms, and obviously exceeds that of the same atoms in the glass.

In the experiment reported here quartz and borosilicate glass were illuminated by a high-intensity light beam from a ruby laser, and the number of photoelectrons was measured as a function of the laser output power. A schematic diagram from the experimental setup is shown in Fig. 1. The light pulse from the laser was monitored with a photoelectric tube, which observed the scattered light from the tube window that housed the 6 mm thick borosilicate glass or quartz plate. The pulsed electron current from the cathode was collected by the anode and measured through a resistor that observed the voltage pulse with a 545-A Tektronix oscilloscope.

The intensive light beam was produced by a ruby laser cooled by boiling liquid nitrogen. The wavelength of the output light was 6943 Å, and the energy emitted through the unsilvered end of the ruby rod was between 0.2-4 joule per flash of the pumping lamp. The power supply charges a bank of condensers (475 μf) to 2000-4000 volts. The output energy measured by a TRG Ballistic thermopile as function of the voltage on the capacitors is shown in Fig. 2. The output light beam from the laser after going through a filter (Corning 366) for filtering out the ultraviolet light from the flash tube was focused to the surface of the glass or quartz plate. The beam spot on the surface was estimated about 1 mm^2, and the average pulse length was about 1.4 msec. The photon flux from

the laser as a function of the output energy is shown in Fig. 3. The average number of electrons per pulse as a function of the output energy is depicted in Fig. 4 and as a function of the average field strength ($\sim \sqrt{\text{average energy}}$) in the beam is shown in Fig. 5 for glass and quartz. From Fig. 5 one can see that the number of electrons from glass and quartz is an exponential function of the field strength, and the electron yield is an order of magnitude higher for glass than for quartz. In Fig. 6 the delay time between the maximum of the monitor signal and the maximum of the electron current are depicted.

As indicated earlier, in the case of the low light intensity experiments on photoelectron emission from borosilicate glass, it has been shown that the photon energy must exceed 4.9 electron volts. In the present experiment electron emission was observed with 1.78 electron volt photons. Thus the present experiments cannot be explained purely on the basis of the photoelectric effect. To give an explanation of the observed electron emission one might investigate four different effects which might conceivably occur.

1. Photoelectric emission with highly decreased quantum efficiency
2. Three or more photon excitations
3. Third harmonic generation and absorption in the dielectric
4. Thermal breakdown in the dielectric surface

1. According to the theory of the photoelectric emission the minimum frequency which can produce a photoelectron is that frequency for which the quantum energy equivalent of the work function

$$\nu_{min} = \frac{e\Phi}{h}$$

It is observed that atomically clean glass and quartz surfaces can remove electrons from clean metal surfaces of work function of the order of 5 volts. Therefore, the work function of the glass surface has to be the same or larger than the metals. This was observed by Rohatgi, who found that the threshold for photoelectric emission for glass lies between 4 and 4.9 electron volts. It is perhaps not unreasonable to assume[2]

that at room temperature many surface imperfections do exist on the glass surface in the form of O^- ions from broken double oxygen linkages and, in addition, quite a few quasi-neutral O atoms. These sites ($\sim 10^{12}/cm^2$) with oxygen having sufficient electron affinity can take up free electrons from the metal, or they can bind moving electrons in the glass and form O^- or $O^=$ ions in states to bind Na^+ ions. Consequently, because the energy of the photons is smaller than the work function of the glass and quartz surfaces, direct photoemission cannot occur.

2. If the incident light intensity is large even when the photon energy is less than that of the energy gap (here, work function), multiple-photon excitation might occur, and electrons can be liberated from the dielectric surfaces. In this experiment a three-photon excitation would be needed for one photoelectron emission.

However, even under the most optimistic conditions the efficiency of this effect[3] is $(E_\ell/E_{at})^3$ where E_ℓ is the electric field in the light wave and $E_{at} \approx 3 \times 10^8$ v/cm is a measure of the average atomic electric field in the dielectric. In this measurement, for example, if the peak electric field is 1.85×10^4 v/cm when the output energy is 1.4 joules, then

$$(E_\ell/E_{at})^3 = \left(\frac{1.65 \times 10^4}{3 \times 10^8}\right)^3 = 1.67 \times 10^{-13}$$

where the peak field strength E_ℓ in the light beam is calculated from the following formula

$$E_{peak} = \sqrt{3}\left(\frac{2W}{\epsilon_o c T S}\right)^{\frac{1}{2}}$$

where W is the output energy per pulse, T is the pulse length and S is the size of the beam at the dielectric surface.

The expected number of electrons per pulse at the output energy of 1.4 joules in the case of glass is

$$N_e = N_{photon}\left(\frac{E_\ell}{E_{at}}\right)^3 = 4.8 \times 10^{18} \times 1.67 \times 10^{-13} = 8 \times 10^5$$

The measured electron number is 5.4×10^8, which is a factor of $\sim 10^3$ larger than that expected from multiple photon excitation processes.

3. In the case of harmonics generation and absorption it is essential that the crystal lack a center of inversion and that it be transparent at the frequencies of the harmonics, but the third harmonic has a large probability of producing photoelectrons from the surface. The harmonic generation was observed in quartz[4] but not in glass. Therefore, it is ruled out as a possible explanation for this experiment.

4. The most probable explanation of the experimental results is that the electrons are coming from the thermal breakdown that has occurred at the dielectric surface. The theoretical treatment of the thermal breakdown in dielectrics might start with the diffusion equation

$$c_v \frac{dT}{dt} + \text{div}(K \text{ grad } T) = \sigma E^2$$

where c_v is the specific heat per unit volume, K is the thermal, σ is the electrical conductivity of the material, T is the temperature, E is the electrical field strength at any point within the specimen, and t is the time. The equation expresses the fact that the joule-heat dissipated within the dielectric partly is conducted away and partly increases the temperature. However, when the breakdown occurs quickly the heat conduction toward the surroundings can be neglected, and the diffusion equation reduces to the following simple equation

$$C_v \frac{dT}{dt} = \sigma E^2$$

If one supposes that the absorbed heat energy on the surface (~ 10 Å thick) is consumed by boiling off electrons N_i and then using the measured thermal delay line data t_i the number of electrons can be calculated using

$$N_i \frac{W}{t_i} = \sigma E_i^2 V$$

where W is the surface work function and V is the interaction volume

($V = 10^{-15}$ in^3). Then the number of electrons when σ is an exponential function of the temperature[5] in the following form

$$\sigma = \sigma_o \exp(\frac{-\varphi}{kT}) = 1200 \exp(\frac{-.96}{kT})$$

and with this

$$N_i = \frac{\sigma \cdot E_i^2 V t_i}{W} \exp\left[\frac{-\varphi}{kT}\right]$$

where φ is called the activation energy of the electrical conduction. ($\varphi = .96$ electron volts for glass.)

Using this formula from the measured delay time t_i, number of electrons N_i, and field strength E_i, the temperature and the conductivity can be calculated. Table I shows these values.

Figure 7 shows the calculated surface conductivity (σ) as function of the field strength (E_i) in the light beam. Because of the exponential dependence of σ on E_i, the electron yield is governed by this exponential factor.

The electron yield from quartz is different because the conductivity and the work function are different; however, these are not known with the same accuracy for quartz as for glass.

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TABLE I

E_i [volt/m]	t_i [sec]	N_i	T_{max} [K°]	$\sigma[\Omega^{-1}\ m^{-1}]$
1.05×10^6	1.20×10^{-3}	1.50×10^7	633	3.63×10^{-5}
1.32×10^6	9.00×10^{-4}	7.80×10^7	691	1.59×10^{-4}
1.45×10^6	7.00×10^{-4}	2.00×10^8	737	4.35×10^{-4}
1.58×10^6	5.75×10^{-4}	4.00×10^8	773	8.92×10^{-4}
1.72×10^6	4.75×10^{-4}	1.00×10^9	827	2.28×10^{-3}
1.85×10^6	3.80×10^{-4}	2.80×10^9	901	6.89×10^{-3}
1.96×10^6	3.20×10^{-4}	5.50×10^9	958	1.43×10^{-2}

LIST OF FIGURE CAPTIONS

FIG. 1--The schematic diagram of the experimental arrangement.

FIG. 2--Output energy measured by TRG(V-2913) ballistic thermopile.

FIG. 3--Laser photon flux vs output energy.

FIG. 4--Average number of electrons per pulse vs output energy.

FIG. 5--Average number of electrons per pulse vs average field strength.

FIG. 6--Delay time between maximum of monitor signal and maximum of electron current.

FIG. 7--Conductivity vs field strength.

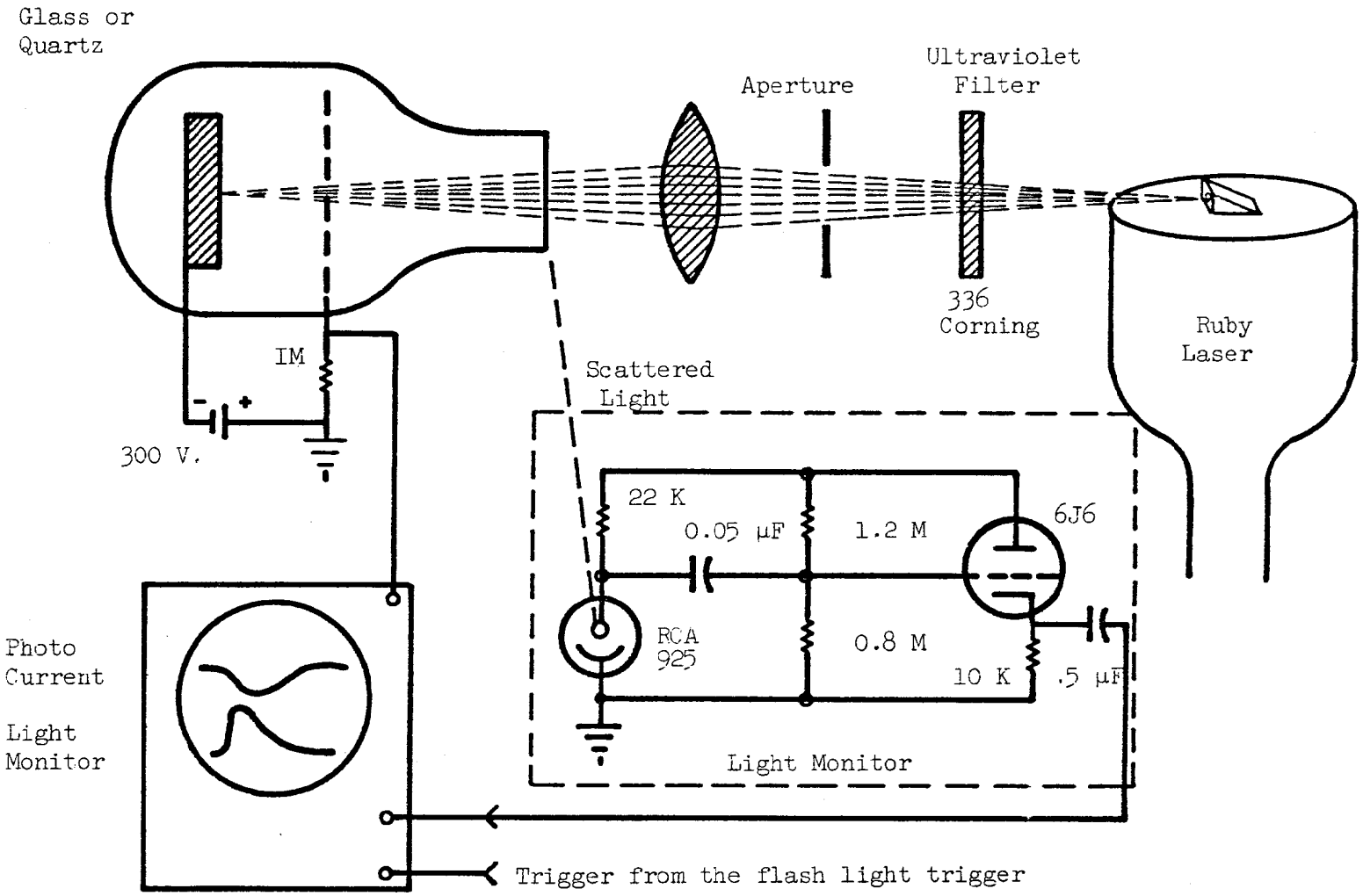

FIG. 1--The schematic diagram of the experimental arrangement.

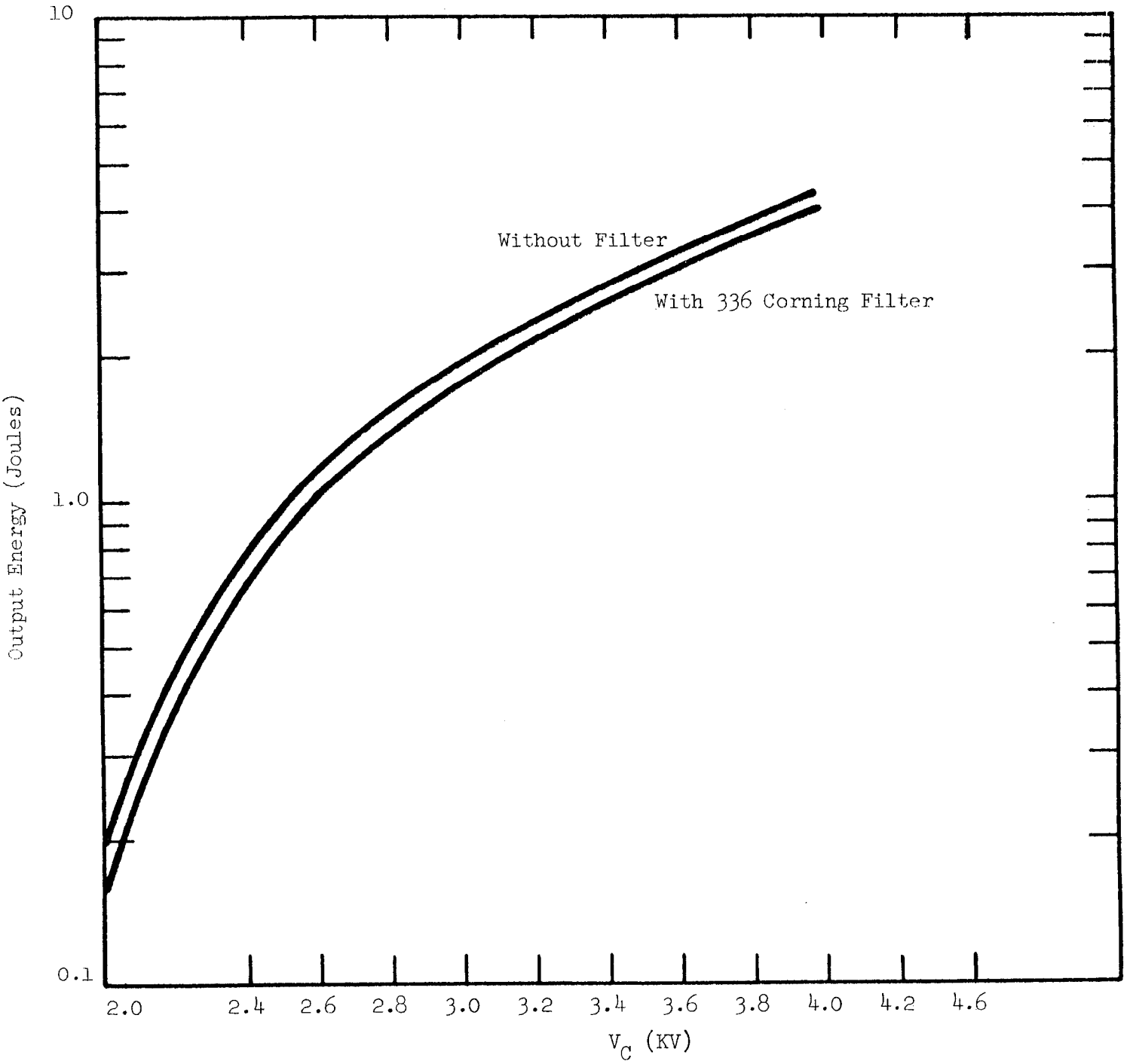

FIG. 2--Output energy measured by TRG(V-2913) ballistic thermopile.

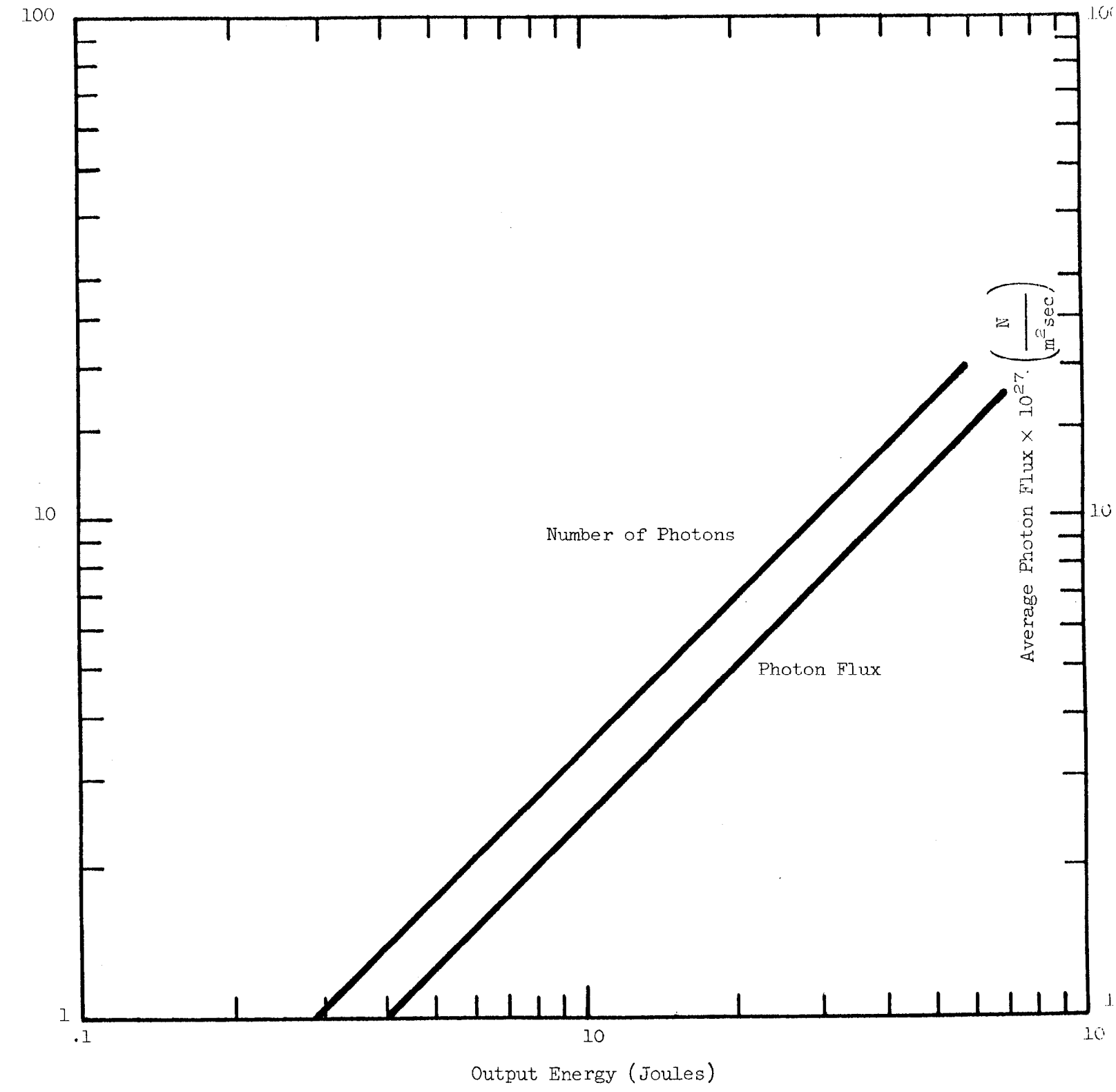

FIG. 3--Laser photon flux versus output energy.

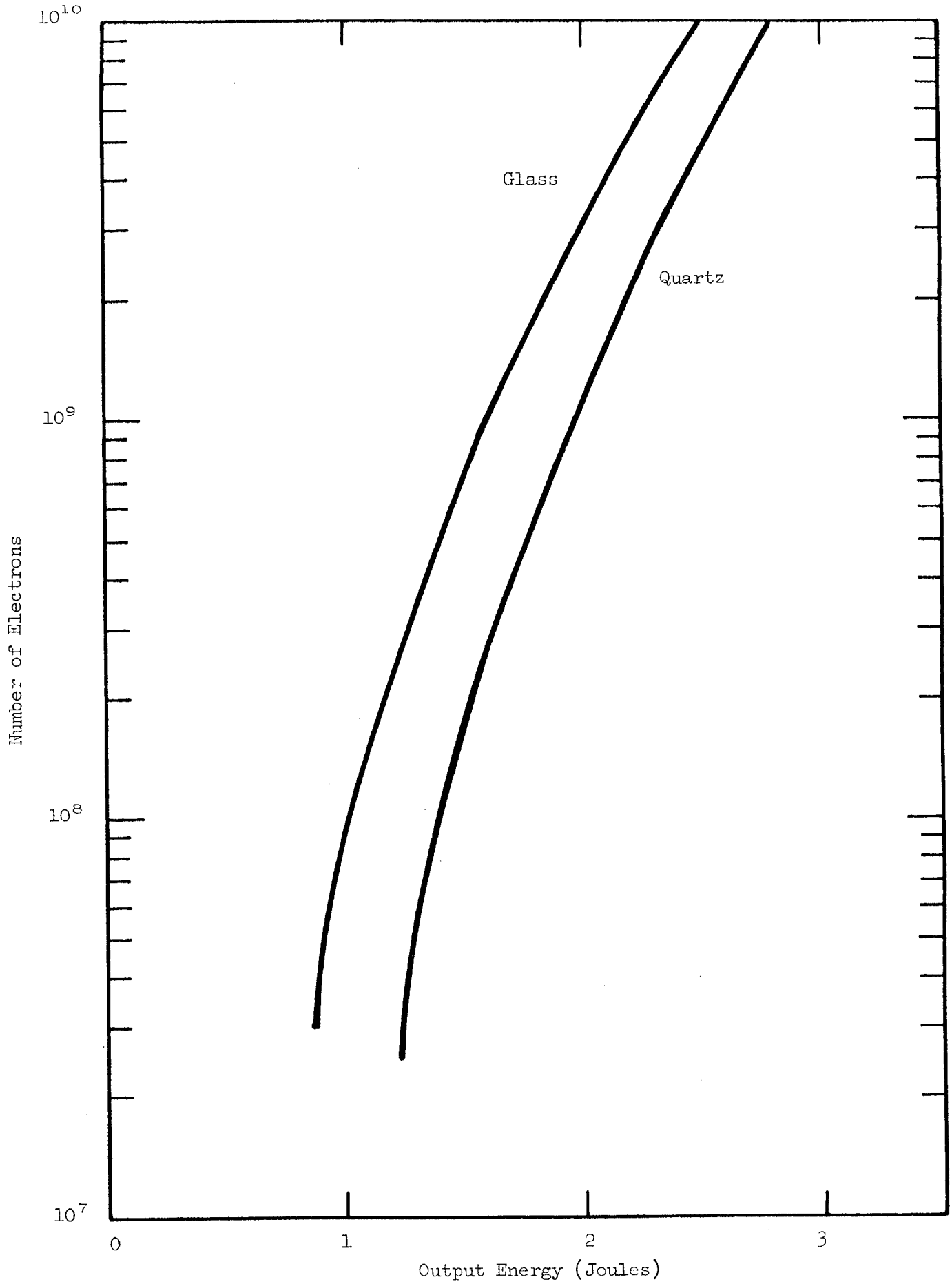

FIG. 4--Average number of electrons per pulse vs. output energy.

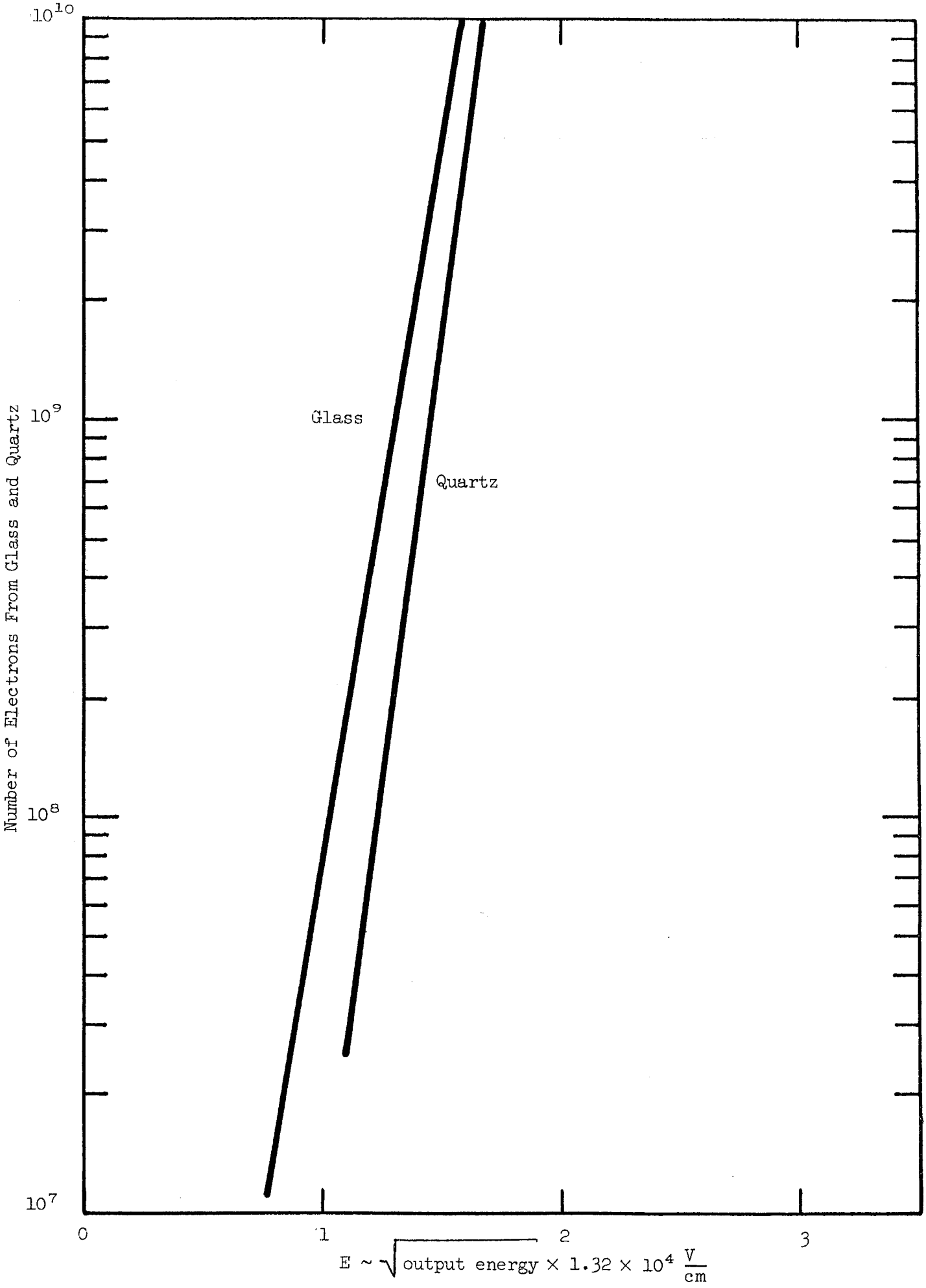

FIG. 5--Average number of electrons per pulse vs. average field strength.

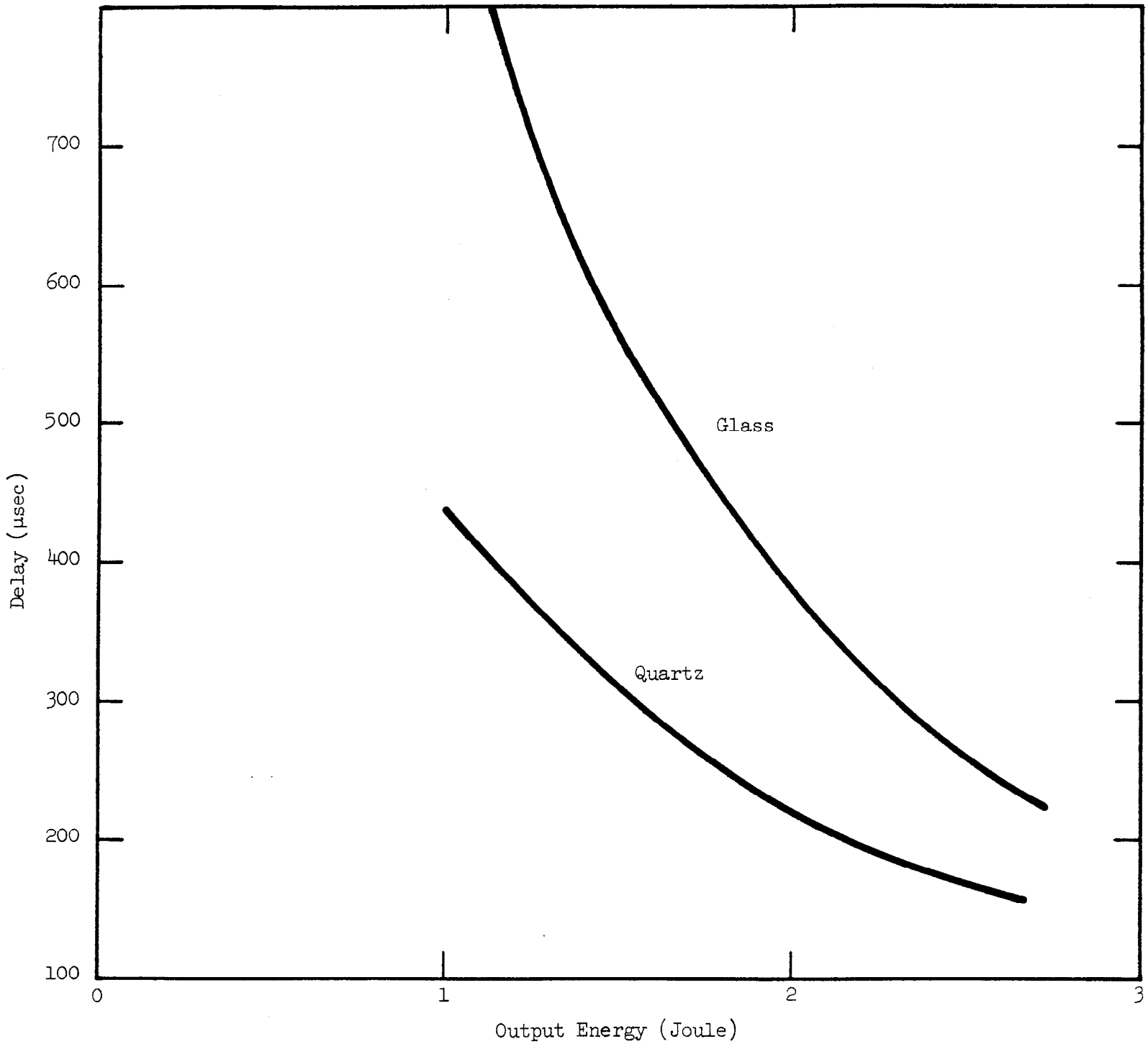

FIG. 6--Delay time between maximum of monitor and maximum of electron current.

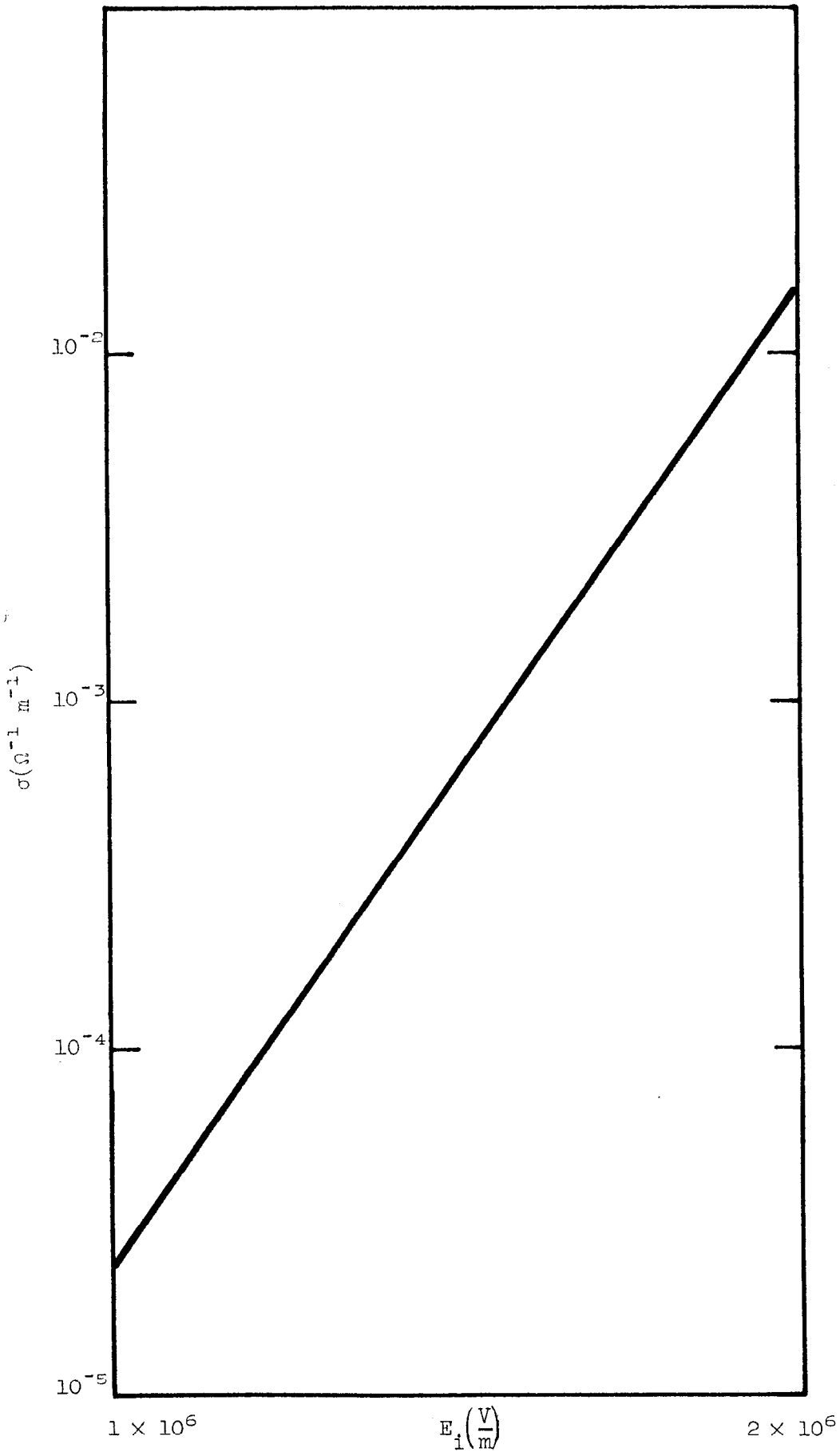

FIG. 7--Conductivity vs. field strength.