SHORT-PULSE HIGH-CURRENT-DENSITY PHOTOEMISSION IN HIGH ELECTRIC FIELDS*)

J. Fischer and T. Srinivasan-Rao
Brookhaven National Laboratory, Upton, NY 11973, U.S.A.

ABSTRACT

We present the experimental results of photoemission studies on thin wires of gold-coated tungsten, held at surface fields in the range of 10^6 to 3×10^8 V/m, and illuminated by 10 ps long, 4.66 eV photon laser pulses. The wire cathodes arranged coaxially in an anode experienced a surface-field enhancement of 10^2 – 10^3 over the applied voltage. We obtained current densities exceeding 10 kA/cm^2 from a 50 μm diameter wire, from a (50×400) μm^2 area, under partially space-charge limited conditions. The quantum efficiency for emission limited cases was in the range of 10^{-5}. For these cases results using 50 μm and 4 μm diameter wires indicated linear dependence of charge density with optical energy density. The emission also scaled linearly with the emitting area. For surface fields above 3×10^7 V/m, a twofold enhancement of emission was observed for a tenfold increase in the field.

1. INTRODUCTION

Novel accelerator concepts such as the switched-power linac (SPL) [1] and the micro-lasertron [2] require current densities exceeding 50 kA/cm^2 from 1 cm^2 area with electron bunch lengths of the order of a few picoseconds. It is difficult to meet these specifications with conventional electron sources. However, photocathodes driven by short, intense light pulses from a laser are more suitable for these applications.

Such photocathodes are also being considered more frequently as electron sources in future colliders. A variety of proposed high energy accelerators [3] and coherent picosecond x-ray sources [4] require electron bunches of extremely low emittance, short duration, and high charge densities. CsSb cathodes have yielded [5] currents of 400 A in ~60 ps from a 1 cm^2 surface. Similarly, GaAs photocathodes have yielded [6] peak currents of 750 A in 60 ps from a 7 cm^2 area. However, both cathodes suffer from the limited life time of the cathode, elaborate preparation process and high vacuum requirement. Furthermore, extension to higher current densities has not yet been demonstrated.

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Our objective to obtain high charge, high charge density, picosecond electron bunches influenced our choices regarding the photocathode and the laser. Metal photocathodes were chosen because of their capability to yield high current densities, fast response time, comparative ease of preparation and maintenance, modest vacuum requirements and ruggedness. Gold coated tungsten cathodes were used in the initial experiments because of their inertness to the atmosphere and ready availability as small wires. The work function of gold ranges between 5.1 and 5.5 eV, and of drawn tungsten wire is 5.25. A frequency quadrupled, pulsed Nd:YAG laser was chosen because of its relatively large photon energy (4.66 eV), simplicity of the system to obtain short pulses of 10 ps, and capability to be upgraded to even shorter pulse durations. The cathodes were maintained at high surface fields, up to 5×10^8 V/m, to simulate the operating conditions for SPL's and electron guns. The following sections describe our experimental arrangement, measurements and results.

2. EXPERIMENTAL ARRANGEMENT

The schematic of the photodiode cells are shown in Figs. 1 and 2. The cells consist of a thin wire as the photocathode and an anode in a coaxial geometry with an anode to cathode gap of 2.5 mm in Cell 1 and 1 mm in Cell 2. DC voltages up to 10 kV can be applied to the cathode via a resistance of 10 - 100 MΩ. The information about the electron emission is derived from the cathode via a capacitor in Cell 1 and directly from the anode in Cell 2. This output can be fed into either a calibrated charge preamplifier, shaping amplifier and pulse height analyzer or coupled from the cell directly to a fast oscilloscope. For these preliminary measurements, gold-coated tungsten wire of 50 μm diameter was used in Cell 1 and a similar wire of 4 μm diameter in Cell 2. Such thin wires give rise to high fields on their surfaces. Surface-field enhancements by a factor of about 100 and 1000 over the applied voltage were obtained with the 50 μm and 4 μm wires, respectively. The wires were illuminated obliquely so that the field lines at the emitting area would not be distorted significantly.

The photons for the photoemitter were derived from a frequency quadrupled Nd:YAG laser, with a photon energy of 4.66 eV, pulse duration of 10 ps, energy up to 1 mJ and a repetition rate of 10 Hz. The experimental arrangement is shown in Fig. 3. The energy of the light pulse on the wire was varied using metallic neutral-density filters. The illuminated area on the wire was changed using either a variable pinhole or a lens in front of the experimental cell.

The SEM pictures of the two wires magnified 1700 and 10000 times, taken before installation in the cell, are shown in Fig. 4. Ridges along the wire axis created by the manufacturing process can be observed, as well as shallower gold granularities of submicron dimensions. These irregularities can influence the photoemission by enhancing local surface fields, varying the local incident angle of light on the wire, and increasing the light absorbing area.

3. MEASUREMENTS AND DISCUSSION

The electron emission for various surface fields and light energy densities was measured for both 50 μm and 4 μm diameter wires. The maximum surface fields for these wires were 5×10^7 and 3×10^8 V/m, respectively. Higher fields caused H.V. breakdown in Cell 1 and high dark currents in Cell 2. The maximum light energies (for controlled emission) on about 0.5 mm length of the wire in Cells 1 and 2 were about 1.2 μJ and 0.5 μJ. Doubling these energies would cause avalanche-type breakdown even at moderate fields. The rise time of the breakdown current decreases rapidly with increasing fields and light intensities. To account for the laser-energy fluctuations, the distributions of laser energy and the corresponding distributions of emitted charge for 400 laser pulses were recorded. The medians of the distributions were selected as data points.

3.1 Charge output vs. light energy

The dependence of charge output on the light energy up to 0.7 μJ from an emitting area of (50×900) μm^2 for various surface fields is shown in Fig. 5. At the lower fields electron emission saturates with increasing light energy, indicating space-charge effects. At higher fields the curves are almost linear up to an emission of ~ 4 pC, indicating direct proportionality between light energy and emission.

The same wire was illuminated with a focused beam over an area of (50×400) μm^2 with higher energies up to 1.3 μJ, resulting in a fourfold increase in the energy density. We see from Fig. 6 that again at higher fields the charge emitted is proportional to the light energy, i.e., nonlinear effects are not yet apparent. The maximum charge obtained was about 26 pC.

Tests at much higher surface fields, up to 3×10^8 V/m, were made in Cell No. 2 on a 4 μm diameter wire illuminated with an unfocused beam via 0.5 mm pinholes on a wire area of (4×500) μm^2. The dependence of the charge and current density on the light energy for this wire is shown in Fig. 7. The fields are now high enough to avoid the space charge effects seen with the 50 μm diameter wire. The output is proportional to light energy indicating once again the absence of nonlinear effects. With this optical arrangement the maximum current density obtained was 7 kA/cm^2. However, with increased optical-energy densities larger current densities can be obtained.

3.2 Current density

The maximum charge of 26 pC obtained in this preliminary experiment can be used to calculate the corresponding current density. If we assume that the electron-pulse duration is that of the laser pulse, measured to be 10 ps with a streak camera, and the emitting area is (50×400) μm^2, then this charge corresponds to a current density of 13 kA/cm^2. This is probably the first time that such high current densities were obtained from macroscopic areas. The actual measurement of electron-pulse duration was limited by the 60 ps rise time of a special fast oscilloscope. However, comparison of measurements of the charge by the calibrated charge-collection method and the observations of pulse shapes and areas with the fast oscilloscope support the assumption of an electron pulse width of approximately 10 ps. We hope that higher photocurrent densities can be obtained below the threshold for breakdown by improving the quantum efficiency, either with lower work-function cathodes, and/or with very high surface fields.

3.3 Charge output vs. surface field

The charge as a function of the surface fields up to 5×10^7 V/m for the 50 µm wire is shown in Fig. 8 for various light-energy densities. The curves A, B and C are for the focused beam with its higher energy densities mentioned before. For the lower energy densities, the curves saturate indicating emission limited operation. At higher energy densities the output rises more sharply with the field, indicating space-charge effects. One could therefore expect that at higher fields (obtained, e.g., by pulsed high-voltage operation) the output can be increased for the same light input, based on space-charge considerations alone.

3.4 Field-Assisted Emission and Quantum Efficiency

Measurements at higher surface fields, up to 3×10^8 V/m, were done with the 4 µm wire. The field dependence of the emitted charge is shown in Fig. 9 for several light energies. At fields of 25-50 MeV/m the charge increases rapidly out of the space-charge regime. For fields above ~10^8 V/m the output increases linearly with the field instead of saturating. The quantum efficiency, which was 1×10^{-5} at a surface field of 0.5×10^8 V/m, increases approximately by a factor of two at the surface field of 2.5×10^8 V/m, for all light levels. This behavior could indicate the onset of a field-assisted photoemission regime. The increase appears linear, probably because of the small range covered here, i.e., only a factor of two. Therefore, a Fowler-Nordheim plot was not useful. The quantum efficiency is expected to increase nonlinearly with the field at surface fields of 10^9 to 10^{10} V/m. We hope to achieve significant field-assisted emission with pulsed fields, or with arrays of microridges giving field enhancements of 10^4 or more.

4. CONCLUSION

We obtained photocurrent densities up to 13 kA/cm^2 from a thin gold-coated tungsten wire from an area of (400×50) µm^2 with modest surface fields of 50×10^6 V/m, using 4.6 eV photon pulses of 10 ps duration. The measured quantum efficiency was about 10^{-5}. At fields above 10^8 V/m an enhancement of the emission was observed, resulting in a twofold increase in the quantum efficiency when the field was increased from 3×10^7 to 3×10^8 V/m. However, to obtain a quantum efficiency approaching one, surface fields of the order of 10^9 to 10^{10} V/m would be needed [7]. Improvements of efficiency and of output currents can also be achieved using lower work function cathodes.

Experiments using these approaches are currently in progress.

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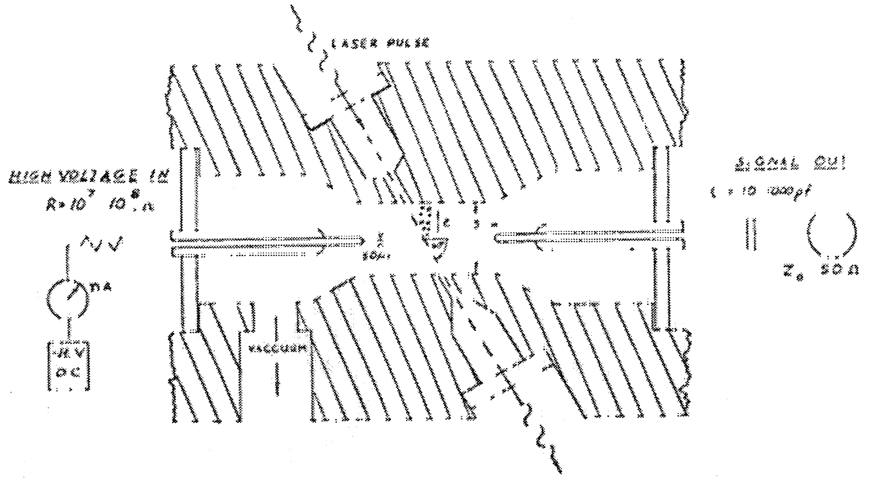

FIGURE 1 Schematic of coaxial photodiode Cell No 1, the 50 μm diameter gold coated tungsten wire cathode in a 5 mm diameter anode enclosure

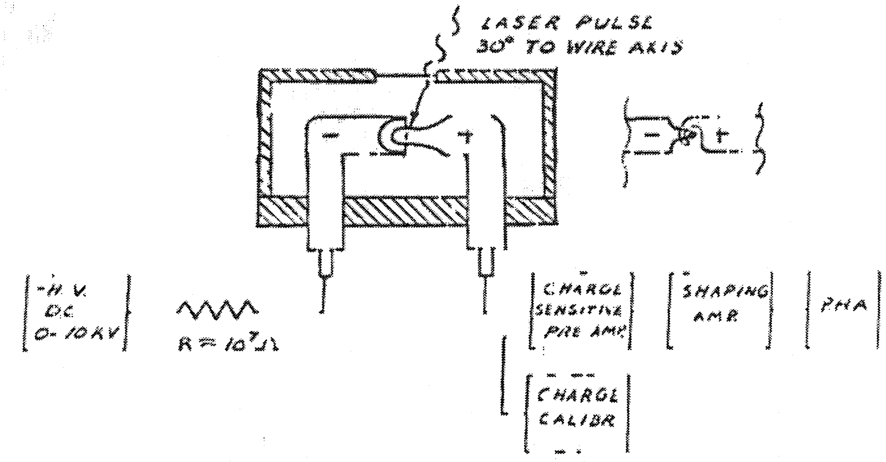

FIGURE 2 Schematic of photodiode Cell No 2, the 4 μm diameter gold coated tungsten wire cathode, held 1 mm from the anode in coaxial arrangement, as seen in the inset

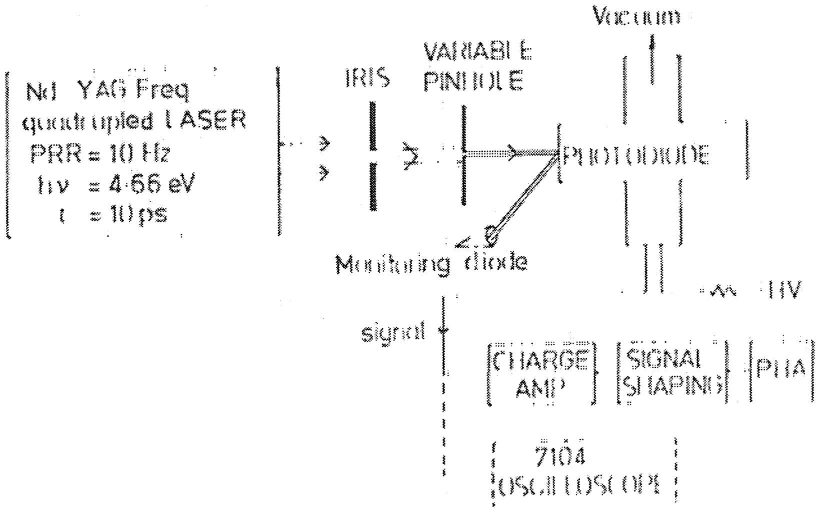

FIGURE 3 Schematic of experimental arrangement The input laser energy density and energy can be changed using metallic neutral density filters, pinholes and focusing lenses

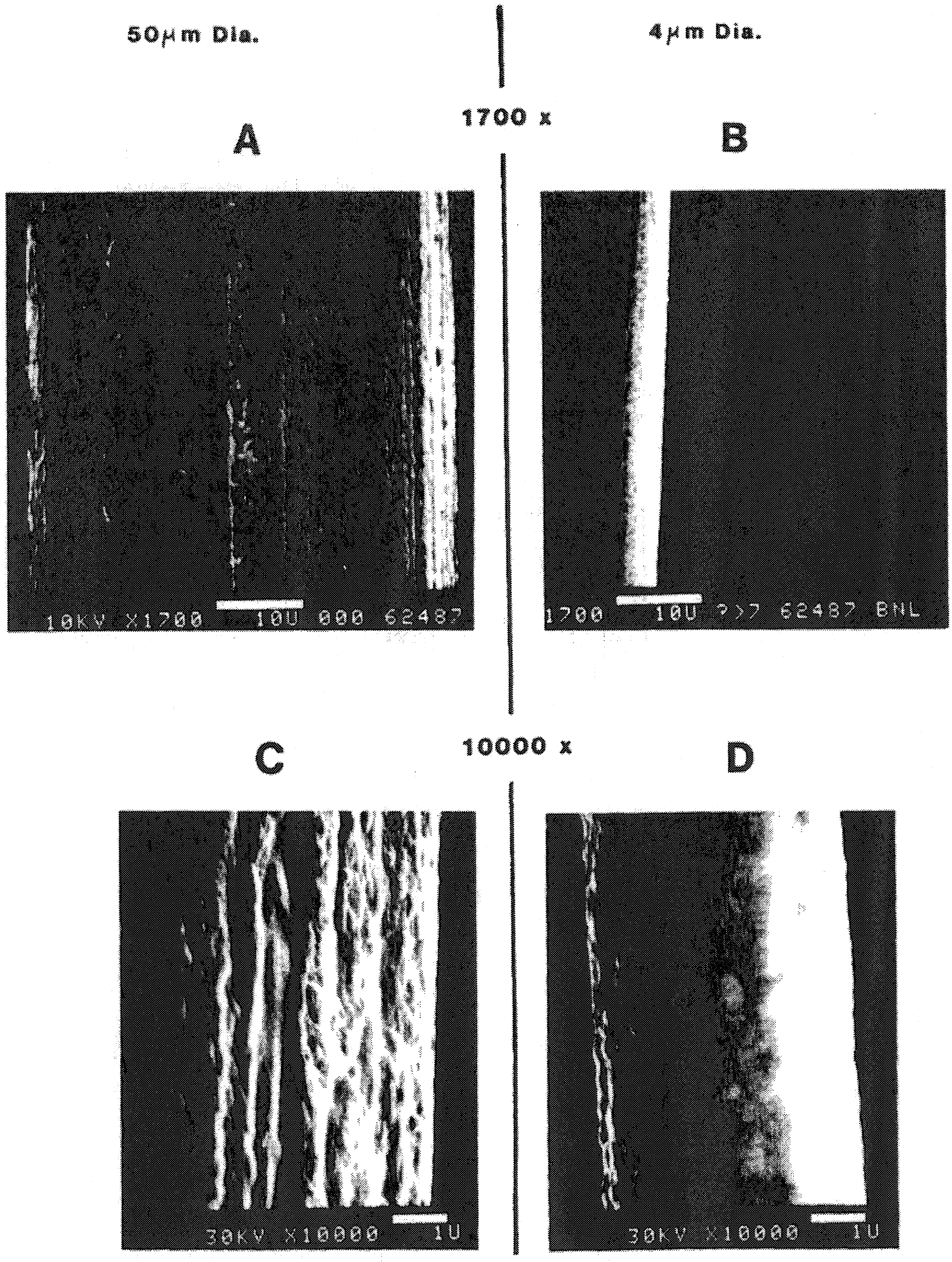

FIGURE 4. SEM pictures of the wire cathodes before installation in the cells. Figs. A and B are the 50 μm diameter and 4 μm diameter wires, respectively, magnified 1700 times. Figures C and D are the same wires magnified 10000 times. Ridges created by the manufacturing process and shallower gold granularities are evident.

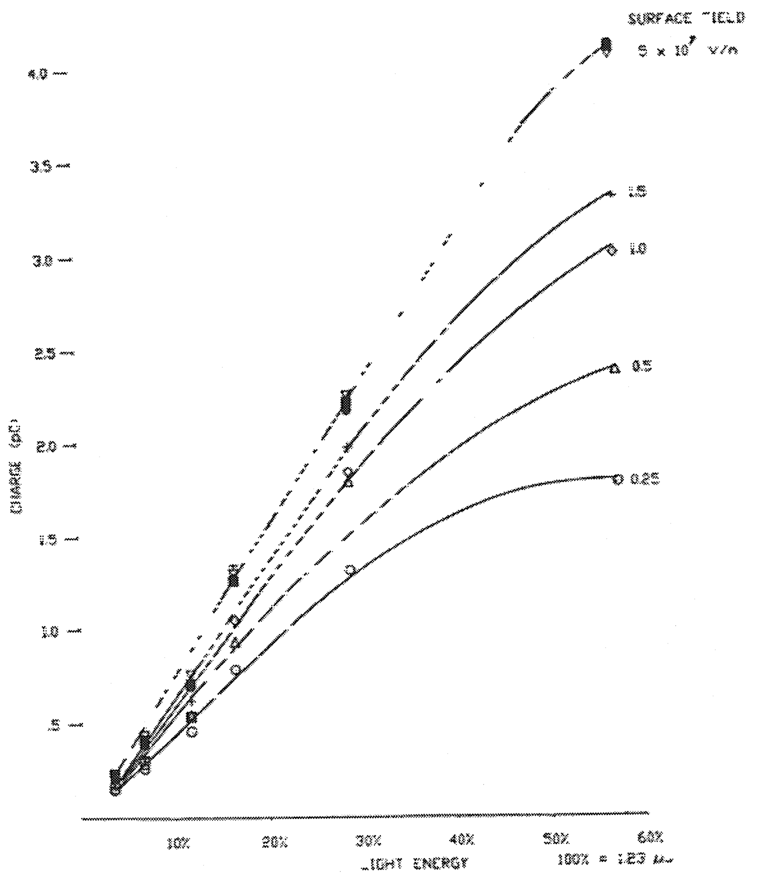

FIGURE 5. Emitted charge vs. light energy for various surface fields for the 50 μm wire. The maximum energy on the wire is about 0.7 μJ on an area of (50×900) μm²

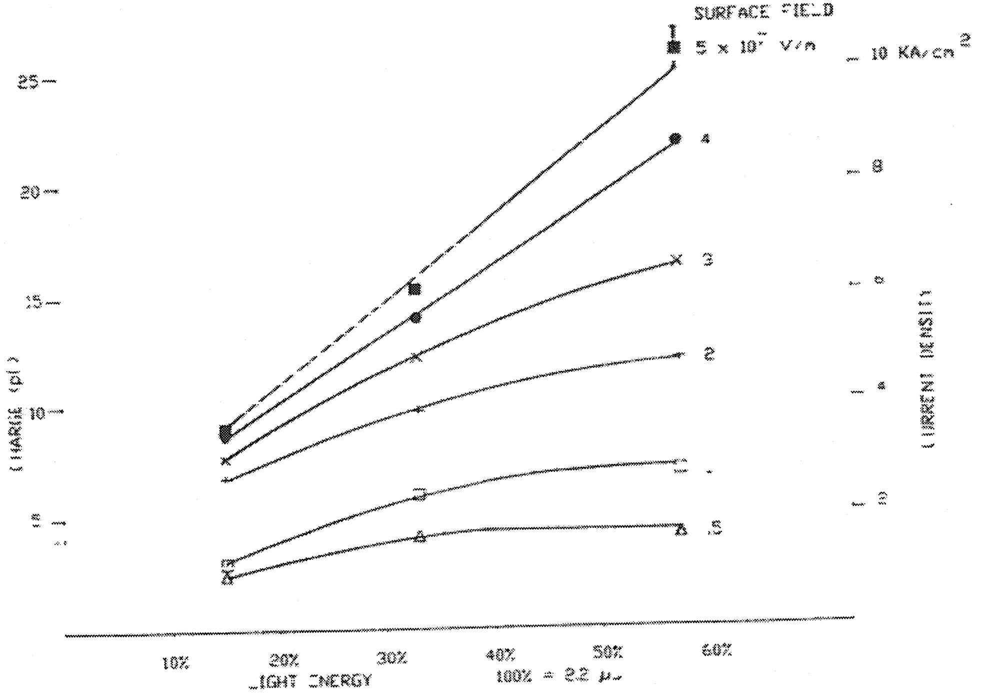

FIGURE 6. Emitted charge vs. light energy for various surface fields for the 50 μm wire. The maximum energy on the wire is about 1.2 μJ on an area of (50×400) μm²

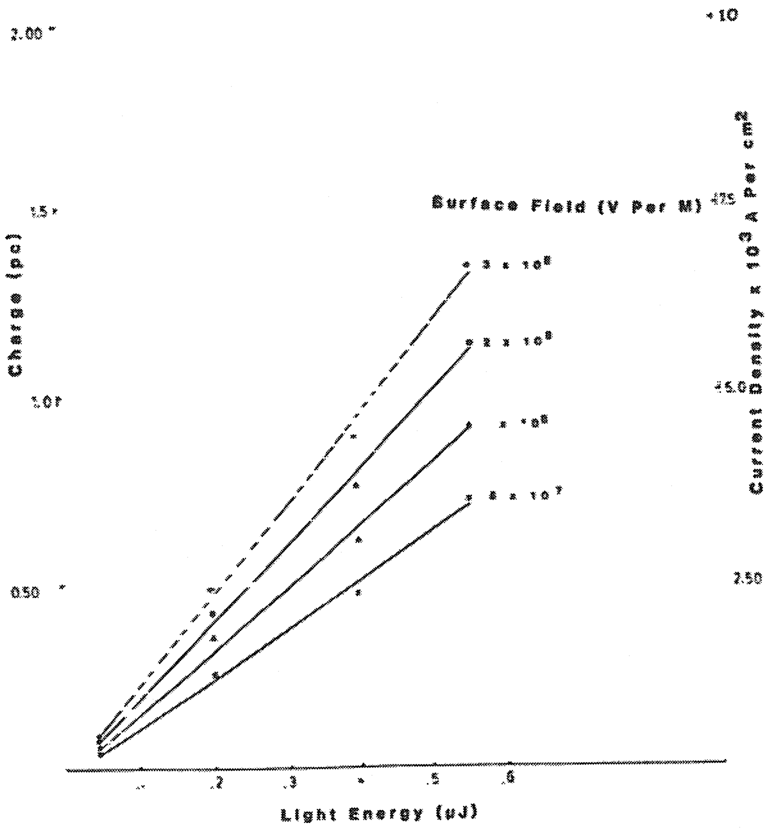

FIGURE 7. Dependence of emitted charge and current density on the light energy for the 4 μm diameter wire at various surface fields. The maximum energy is 0.6 μJ on a (4×500) μm² area.

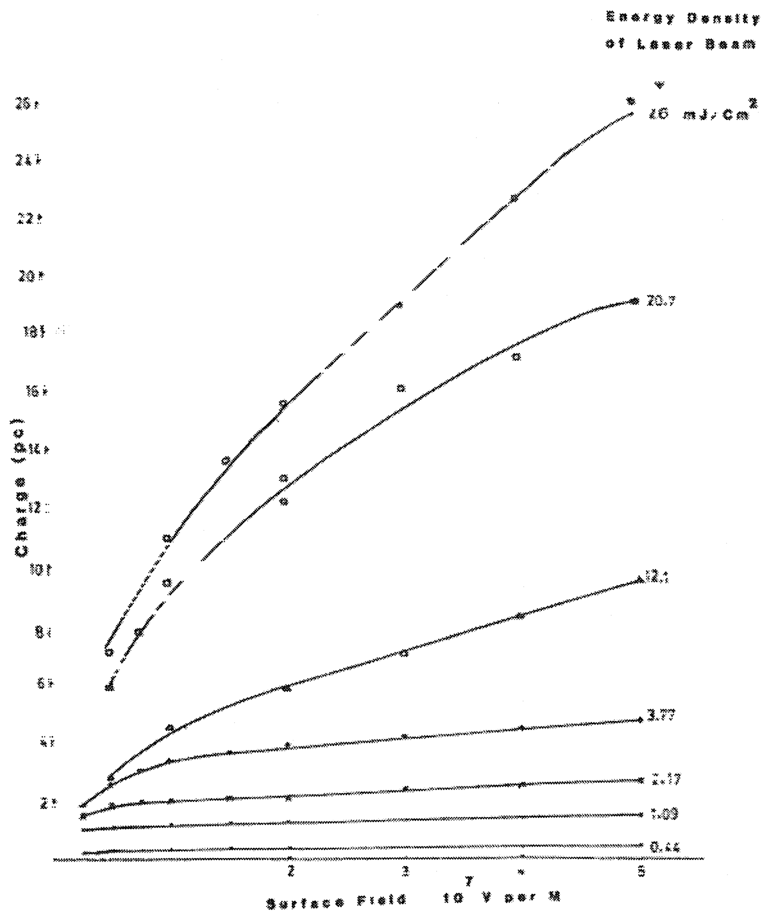

FIGURE 8. Emitted charge vs. surface field for the 50 μm diameter wire, for various light energy densities. The illuminated length of the wire for curves A, B and C is 400 μm and for D, E, F and G, 900 μm.

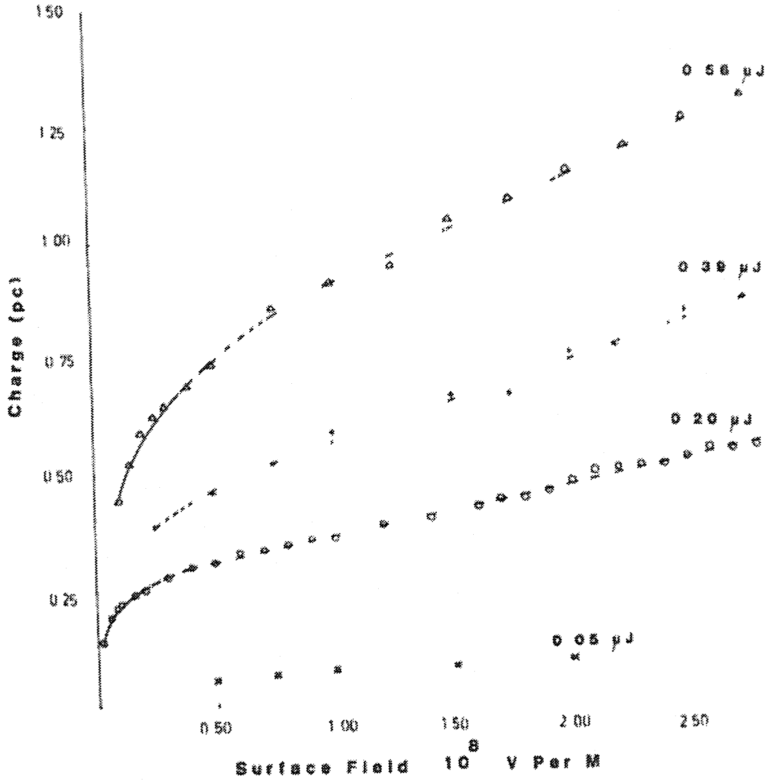

FIGURE 9 Emitted charge vs surface field, with light energy as a parameter, for the 4 μm diameter wire The illuminated length of the wire is 500 μm