SLAC-PUB-1446
(I/A)
June 1974

A PULSED SOURCE OF SPIN POLARIZED ELECTRONS BY PHOTOEMISSION FROM EuO*

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ABSTRACT

It is experimentally demonstrated that a light pulse of 1 μsec duration and $\gtrsim 10$ Watts peak power striking the surface of ferromagnetic EuO held at $\sim 10^{o}$K does not adversely affect the spin polarization of photoelectrons emitted from this material. It is thus possible to obtain a pulsed beam of polarized electrons suited for injection into a high energy accelerator. It is expected that considerably more than 10^{9} electrons/pulse with a polarization of 80% can be obtained, with emittance ≤ 7 mrad-cm as required for linear accelerators.

(Submitted to Nucl. Instr. and Meth.)

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* Work supported in part by the U.S. Atomic Energy Commission and by the Schweizerischer Nationalfonds.

I. INTRODUCTION

The fact that electron spins have a preferred orientation in a magnetized solid can be used to obtain a source of spin polarized electrons. A high spin polarization has been observed both for electrons photoemitted from EuO[1] and for electrons field emitted from EuS coated W tips[2], although at present the photoemission source is more practical. In addition to electron emission from solids, there are a number of other sources of polarized electrons of varying quality; one of the most developed, photoionization of polarized alkali atoms, has been described by Hughes, et al. and compared to existing sources at that time (1972).[3] In this work we investigate a very promising polarized electron source employing photoemission from a solid, namely EuO.

The electron spin polarization P is defined as the expectation value of the Pauli spin operator along a given direction in space, for example the z direction defined by an applied magnetic field:

$$P = \langle \sigma_z \rangle = (N\uparrow - N\downarrow) / (N\uparrow + N\downarrow) \qquad (1)$$

where $N\uparrow$, $N\downarrow$ are the respective numbers of spin up and spin down electrons (magnetic moment respectively parallel and antiparallel to the magnetic field direction). The degree of polarization from a photoemission source depends on a number of factors including the electronic structure of the magnetic solid, the wavelength of the photoexciting light, and the applied magnetic field and geometry of the sample as will be discussed below. The number of electrons obtainable depends on the light intensity and the photoelectric yield at a given photon energy as follows:

$$n_e(\omega) = Y(\omega)\, I_p(\omega) \qquad (2)$$

where Y is the yield in electrons per incident photon, and I_p is the photon current. In the case of EuO, $Y \sim 3 \times 10^{-3}$ electrons / incident photon in the photon energy range 4 eV $< \hbar\omega <$ 6 eV. [4]

There has been increased interest recently in a source of polarized electrons compatible with the pulsed injection mode of electron accelerators. At the Stanford Linear Accelerator Center, for example, electrons are injected at the rate of 360 pulses per second, each pulse being about 1 μsec long. A suitable source of polarized electrons could make feasible such experiments as the measurement of the spin structure of the scattering amplitude for deep inelastic scattering of polarized electrons by polarized protons and the study of possible contributions from weak,parity violating interactions in the scattering of polarized electrons by unpolarized protons in a liquid hydrogen target. Experiments involving polarized targets require about 10^9 electrons per pulse and those involving unpolarized targets could easily use 100 times more.

While dc polarized photocurrents equivalent to the average of 360 pulses of 10^{10} electrons each have been achieved, [1] questions arise when a pulsed source is considered. Does the 10 W peak power (approximate requirement for 4×10^{10} electrons) absorbed during 1 μsec heat up the EuO locally such that the magnetism is destroyed ? It is not possible to calculate the temperature rise because of uncertainties in the exact mechanism of heat dissipation, as well as in the parameters describing the physical properties of EuO. However, estimates range from 15 - 125^{o}K. Since the Curie temperature of EuO is 69^{o}K, a temperature increase of 15^{o} above the 4.2^{o}K operating temperature would be tolerable while a 125^{o}K increase would clearly not be. The purpose of the work we report here was to explore experimentally the pulsed mode of operation and determine if the

polarization is reduced by heating effects.

In the next section we discuss briefly the electronic structure, the magnetic properties, and photoemission from EuO. An overview of the apparatus with a special discussion of the pulsed lamp and the Mott scatterer is presented in Sec. III. In Sec. IV we present the results using the pulsed lamp and discuss the implications for a pulsed polarized electron source.

II. EuO

EuO is a ferromagnetic semiconductor that crystallizes in the NaCl structure and has a Curie temperature of $69^{\circ}K$. The positively charged Eu^{++} ion has a strictly localized spin - only moment due to the half-filled 4f shell ($^8S_{7/2}$ configuration). The occupied valence band is formed of the O^{--} anions and is separated by an energy gap of 4 eV from the empty conduction bands made up of the 6s and 5d wavefunctions of the Eu^{++} ions. The localized 4f levels lie in this gap ~ 1.2 eV below the bottom of the conduction band as seen in Fig. 1. Intrinsic and extrinsic impurity states also lie in the gap and may exhibit a polarization due to interaction with the 4f electrons.

An electron is photoemitted when a photon of sufficient energy excites the electron to a state above the vacuum level E_∞ whence it can escape from the solid into the vacuum. The vacuum level is located 1.8 eV above the Fermi level E_F which in turn is 0.1 eV below the bottom of the conduction band.

All of the 4f electrons have spins aligned in the direction of the magnetic field if a sufficiently large field is applied to line up the ferromagnetic domains. The demagnetizing factor of the crystals is $\sim 1/3$, so the bulk is expected to saturate with an applied field of 1/3 the saturation magnetization of 24 kOe.

If the photon energy is less than 6 eV, the 4f electrons but no valence electrons would be photoemitted, and a polarization of 100% would be expected on the basis of this simple model. In fact, the polarization is decreased if nonmagnetic impurities are present and contribute to the photocurrent. Further, the polarization is reduced by the existence of a nonsaturated sheet at the surface, at which electrons from deeper inside the material undergo spin disorder scattering. The depth of origin[5] of electrons excited 1-3 eV above the vacuum level is 50-100 Å in EuO[4] even though the light absorption depth is at least 400 Å for 4 eV $< \hbar\omega <$ 6 eV.[6] It has been estimated[7] that spin exchange scattering from a single paramagnetic surface layer could reduce the polarization of the photoemitted electrons from EuO by as much as 50%. On increasing the magnetic field strength, the paramagnetic sheet also becomes magnetized with a resultant decrease in depolarization. The unsaturated surface sheet was postulated to explain previous measurements on EuO, where the polarization did not saturate up to 25 kOe.

When EuO is doped with a trivalent ion such as La^{+++} several changes occur in the magnetic, electrical, and optical properties. Of particular importance for this study are the increases in the polarization, the Curie temperature, and the electrical conductivity. The first two changes can be understood because in EuO the ferromagnetic coupling is due to an indirect Eu-Eu exchange over electrons virtually excited into the 5d states which become occupied on doping and thus increase the ferromagnetic coupling.[8] It is proposed that an analogous effect occurs in the nonsaturated surface sheet. The proposal is based on the observation that on doping the polarization of photoelectrons increases at constant magnetic field. This suggests that on doping the 4f surface spins are

better coupled with the bulk spins.

The increased electrical conductivity on doping is essential for an intense polarized electron source. In an insulating sample, the photoemission is limited by charging of the region near the surface.

In this experiment we used a EuO crystal nominally "doped" with 2% La. In fact, the true La concentration varies over the crystal and is not known, except that the crystal is strongly n-type.

III. APPARATUS

A. Overview

The apparatus consists of the liquid-helium-cooled photoemitter in a homogeneous magnetic field and ultrahigh vacuum, a light source, an electron accelerator system, and a Mott scatterer or analyzer of the polarization as seen in the schematic diagram of Fig. 2. The EuO crystals, typically cubes ~ 4 mm on a side, are mounted in stainless steel holders. Provision is made to hold up to 20 of these in a wheel in the apparatus. The wheel may be turned to position a given crystal below the cleaving section and a gripper can pull the crystal up to the anvil in position for cleaving. A 1 mm slice is cleaved from the EuO crystal to obtain an atomically clean(100) surface. The crystal is then returned to the wheel, which is turned so that a second gripper can pull the cleaved crystal into the measuring position in the center of a 30 mm-bore superconducting coil.

The electrons which are photoemitted when the light impinges on the sample are extracted from the magnetic field region by a series of electrodes. The

cylindrical condenser changes the direction of the electron beam so that the polarization is transverse to the electron momentum as required for Mott scattering. The electrons are accelerated to 100 KeV where they are scattered from a thin Au foil and the polarization is measured. The Mott scatterer and counting electronics are discussed in more detail below. For the dc measurements a high pressure Hg-Xe arc lamp was used. The optics were arranged so that the electron beam could be adjusted in the dc mode ; then with a small mirror adjustment the dc lamp could be replaced by the pulsed lamp.

B. Pulsed Lamp

The pulsed lamp was a high pressure (5 atm) sealed Xe lamp with two W electrodes 4 mm apart.[9] Under typical operating conditions of 2.7 kA peak current the spectrum of the lamp is relatively flat from 5-6.5 eV. The lamp was pulsed by the circuit shown in Fig. 3. For a pressure of 0.4 kp/cm^2 N_2 in the spark gap and 20 kV input voltage, the lamp flashed with a repetition rate of 6.7 Hz.

The pulse shape as shown in Fig. 4 had a peak current of 2.7 kA and a 1.2 μsec FWHM. Similar lamps have been run with the SLAC modulator at 180 pps.[9]

Only a fraction of the lamp output actually reached the sample. The optics of this versatile research apparatus could be improved upon in an apparatus designed primarily as an electron source. The mirror system accepted only $\sim 4 \times 10^{-2}$ steradian ; in addition, only about 5% of the image of the lamp went through the aperture. Nevertheless, $\sim 10^{13}$ photons per pulse with energy greater than the 4f threshold were focussed into a 2.3 mm^2 spot on the sample to produce 3×10^9 electrons/pulse.

C. Mott Scatterer

Mott[10] first pointed out in 1929 that elastic Coulomb scattering of electrons from heavy atoms depends on the spin state of the electrons through LS coupling on scattering. In this experiment, the electrons which have been accelerated to 100 KeV are scattered from a gold foil, which is thin to minimize multiple scattering. Two Si surface barrier detectors[11] measure the intensities (N_1, N_2) at scattering angles $\pm 120 \pm 3^{o}$ to give the scattering asymmetry

$$A = (N_1 - N_2) / (N_1 + N_2) \quad .$$

The polarization is related to A by[12]

$$A = (A_a + PS) / (1 + A_a PS) \quad . \qquad (3)$$

S is the Sherman function which has a broad maximum at a scattering angle of 120^{o} for 100 KeV electrons.[13] A_a is the apparatus asymmetry which arises from (1) slight asymmetries in the sensitivity and orientation of the detectors and (2) variations in the angle and position of incidence of the beam on the gold foil (limited by apertures which define the beam). The first contribution to A_a can be measured and eliminated by reversing the magnetic field B at the sample. The second contribution to A_a can give rise to a small systematic error to the extent that the beam angle and position change on reversal of B. For this reason, there are two detectors in the forward direction at $\pm 45^{o}$ where $S \sim 0$ in order to monitor A_a.

The Sherman function is well known from theoretical calculations which have been experimentally verified.[13] The Sherman function for infinitely thin foils S_0 is tabulated. For 100 KeV electron scattering at 120^{o}, $S_0 = 0.39$.

The experimental foils must be calibrated to determine the effective Sherman function S. A wheel in our apparatus held 6 foils with nominal thicknesses varying from 150 $\mu g/cm^2$ to 460 $\mu g/cm^2$ as determined before mounting in the wheel. The effective thickness of the foils was determined in situ by letting an electron beam of constant intensity fall on a foil and measuring the sum of the electrons I_B backscattered into the detectors at $\pm 120^o$. For thin foils where multiple scattering is negligible, there is a linear relationship between nominal foil thickness and counting rate I_B.

The measured Mott asymmetry A is related to the asymmetry for a zero thickness foil A_0 by

$$\frac{A_0}{A} = 1 + \alpha d \qquad (4)$$

where d is the foil thickness and α is a constant. A_0 and α can be determined by plotting A^{-1} as a function of d where we found $\alpha = 0.0026$ and $A_0 = 0.225$. If the measurements are made with a beam of constant polarization (and care is taken to eliminate A_a), then

$$\frac{A_0}{A} = \frac{S_0}{S} = 1 + \alpha d \quad . \qquad (5)$$

The relative Sherman function S_0/S is shown in Fig. 5. The S determined for the foil used in this experiment was 0.28.

The counting electronics following the detectors was different depending on whether the dc lamp or the pulsed lamp was used. With the dc lamp single electrons were counted. The output of a detector went through a preamplifier, amplifier, and pulse height analyzer to the counter. In the case of the pulsed lamp, the many electrons in the 1.5 μsec burst could not be counted singly because the resolution is limited by the ~ 1 μsec amplifier output pulse width.

Instead the output of the amplifier was fed to a converter which gave a pulse train of length proportional to the height of the input pulse. The converter was gated by a delayed gate generator which was triggered by a signal from a pickup coil near the lamp. Because the pulse height analyzer was not used in this mode, a small background was measured even in the absence of photocurrent and was considered in evaluating the data.

IV. RESULTS AND DISCUSSION

The results of this experiment are presented in Table 1. No significant difference between the P of electrons excited by the pulsed lamp and the P of electrons excited by the dc lamp was observed. The uncertainties given in the table represent ± one standard deviation in the counting statistics. In fact, a further systematic error of up to ± 2% due to slightly varying A_a with beam adjustment may be present. The background counting rate during the pulsed measurements varied in the course of the experiment ; the values given in the table are uncorrected for background. With the exception of measurement 1, the maximum correction due to background amounted to + 2% for measurement 5. The pulsed measurement at 4.22 kG was especially sensitive to the background because (1) the polarization and hence the measured asymmetry was lower, and (2) due to beam adjustment difficulties the counting rate for the two magnetic field directions were different by a factor of ~ 2.5 and so also was the background. The measured polarization was 9.8% without correction for background and 18.6% with correction for background.

A test was made to see if unpolarized electrons from the valence bands were excited by the pulsed lamp which produced photons up to energies somewhat

greater than 6 eV. A UG5 filter with a pass band from 3 to 5.5 eV produced no significant difference in the measured P as seen from measurements 3 and 4. A factor of 4 reduction of the pulsed light intensity by simply inserting an aperture in the incident light beam also did not significantly affect the polarization as seen from measurements 5 and 6.

The measurements took place in a period of 8 hours following the cleaving of the crystal in the following order: Measurement No. 3, 4, 5, 6, 2, 1. A check on the polarization for a field of 12.66 kG at the end of the measurement period showed no change in the polarization. The pressure was 2×10^{-9} Torr, which was higher than desirable. Previous measurements at 2×10^{-10} Torr produced both higher yields and higher polarizations. Vacuum conditions are very important because residual gases can condense on the cold surface of the crystal.

The usable intensity of the polarized electron beam depends on its electron-optical properties and how these match the accelerator. In the case of SLAC, the accelerator can accept a 70 keV electron beam with an emittance of 7 mrad-cm (aperture angle × radius). In our experiment, electrons are generated from a finite area in a magnetic field. Because the axial component of the canonical angular momentum $\vec{L} = \vec{v} \times (m\vec{v} + e\vec{A})$ is conserved, electrons produced off-axis will have skewed trajectories in a region of zero magnetic field. The effective emittance in this case can be shown[3,14] to be

$$\epsilon = r_0(E_0/E)^{1/2} + \frac{1}{2}(e/m)\, r_0^{\,2} B_0/v \qquad (6)$$

where e = charge, m = mass, r_0 = distance to axis from point of electron origin, B_0 = magnetic field at electron origin, v = final velocity of electron, E_0 = initial energy of electron and E = final energy of electron. In order for 70 keV electrons

originating in a field of 12.66 kG to have an emittance ≤ 7 mrad-cm, they must be emitted in an area of radius 0.32 mm. The first term in Eq. 6 is negligible relative to the second for these conditions. We measured 3×10^9 electrons per pulse generated from an area of 0.85 mm radius which corresponds to 4×10^8 electrons per pulse with an emittance ≤ 7 mrad-cm at 70 keV.

There is no way to avoid the emittance imposed limitation on the usable light spot size in photoemission from solids when a large magnetic field is present. Increasing the length of the crystal or backing it with an iron rod decreases the demagnetizing factor and the size of the magnetic field that must be applied to achieve a given magnetization. However, $\vec{B}$ is perpendicular to the sample surface, so the magnetic field at the sample surface is unchanged.

Should heating problems occur in EuO at very high light intensities, Fe could be used as the photoemitter. If a fraction of a monolayer of Cs is deposited on the Fe surface to lower the work function to 3-3.5 eV, the average yield over the range $5 \text{ eV} \leq \hbar\omega \leq 6.5$ eV is $\sim 1 \times 10^{-3}$ electrons / incident photon. In a field of 20 kG, the average polarization expected is $\sim 35\%$.[15] The figure of merit of a polarized electron source is $\propto IP^2$. For reasonable values of polarization, the lower polarization can be compensated by a higher intensity unless a higher electron beam current is in itself undesirable as in the case of an experiment with a polarized target. At lower values of polarization, systematic effects on polarization value occuring with polarization reversal become increasingly difficult to detect and correct for.

In conclusion, we have seen that there is no decrease in the polarization of the photoelectrons from EuO + 2% La with a light intensity sufficient to produce 3×10^9 electrons per pulse. Straightforward improvements in the

optics and apparatus design can increase the useful light intensity on the sample by a factor of 100. More than half of the light intensity is in photons with energies below 4 eV, and may be filtered out to minimize heating effects, should they be observed.

V. ACKNOWLEDGEMENTS

We should like to thank Prof. G. Busch for supporting this work. We also want to thank Dr. R. Balzer for making available the pulse height to frequency converter and to Dr. M. Campagna for his help in constructing the Mott scattering chamber. The EuO crystals were kindly supplied by Dr. E. Kaldis.

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FIGURE CAPTIONS

Fig. 1 Energy level scheme for EuO.

Fig. 2 Schematic diagram of apparatus. (1) moveable He cryostat with sample gripper (2) He cryostat (3) liquid nitrogen (4) superconducting coil (5) sample (6) accelerating electrodes (7) rotatable wheel with samples (8) parallel beam shifters (9) plane condenser (10) cylindrical condenser (11) aperture (12) light source (13) gripper for cleaving (14) cleaving blade (15) UHV valve (16) linear motion (17) vacuum interlock (18) ion pumps (19) seven stage accelerator (20) gold foil (21) detectors to measure Mott asymmetry (22) forward detectors to monitor beam.

Fig. 3 Circuit for pulsing flash lamp.

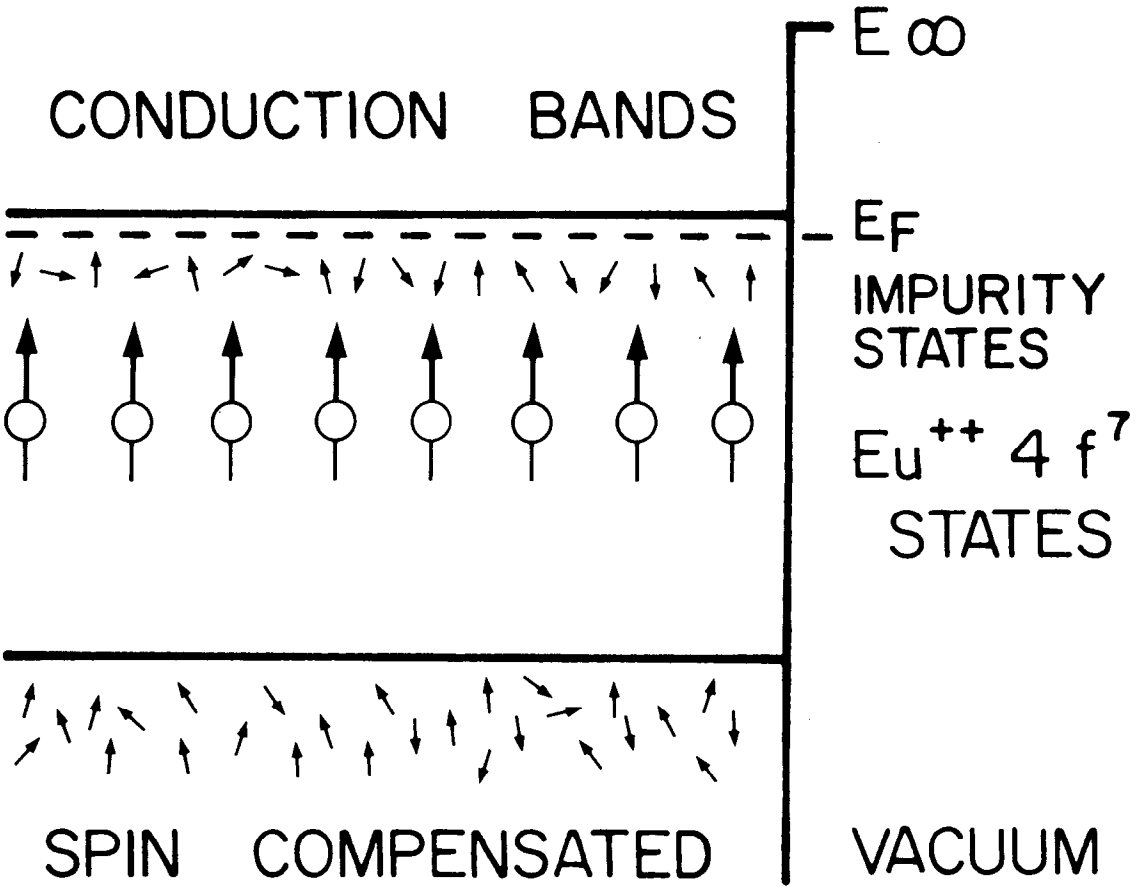
Fig. 4 Lamp pulse shape with 20 kV input voltage and 6.7 Hz repetition rate.

Fig. 5 Relative Sherman function as a function of Au foil thickness.

Table 1. Comparison of Measured Polarization with Pulsed and dc Lamps.

Measurement	Magnetic Field (kG)	Filter	Polarization dc Lamp	Pulsed Lamp
1	4.22	none	20.6±0.4%	(see text)
2	8.44	none	32.5±0.5%	37.3±0.4%
3	12.66	none	55.0±0.3%	57.7±0.4%
4	12.66	UG5	54.1±0.5%	60.6±0.4%
5	21.1	1/4	61.4±0.3%	61.3±0.4%
6	21.1	none	—	58.5±0.4%

ENERGY LEVEL SCHEME OF Eu O



Eu O

2544A2

Fig. 1

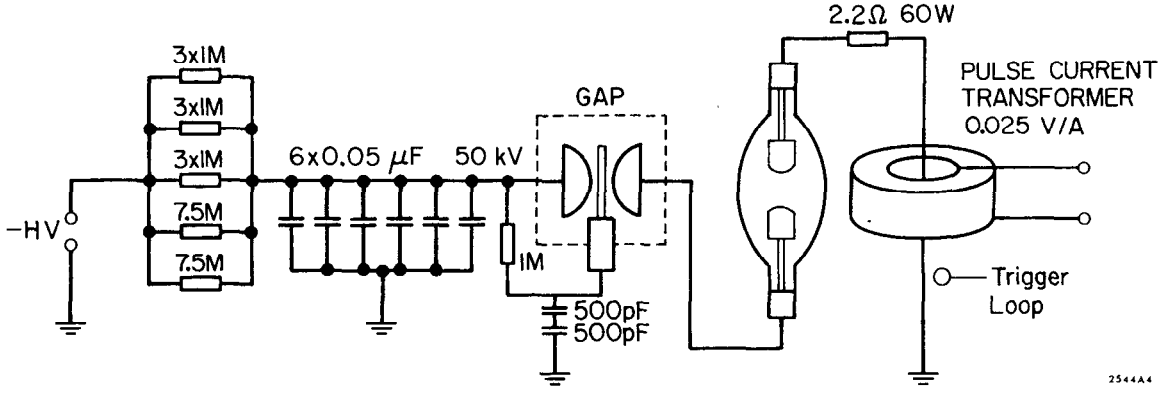

2.2Ω 60W
3xIM
3xIM
3xIM
7.5M
7.5M
-HV
6x0.05 μF
50 kV
GAP
1M
500pF
500pF
PULSE CURRENT
TRANSFORMER
0.025 V/A
Trigger
Loop
2544A4

Fig. 3

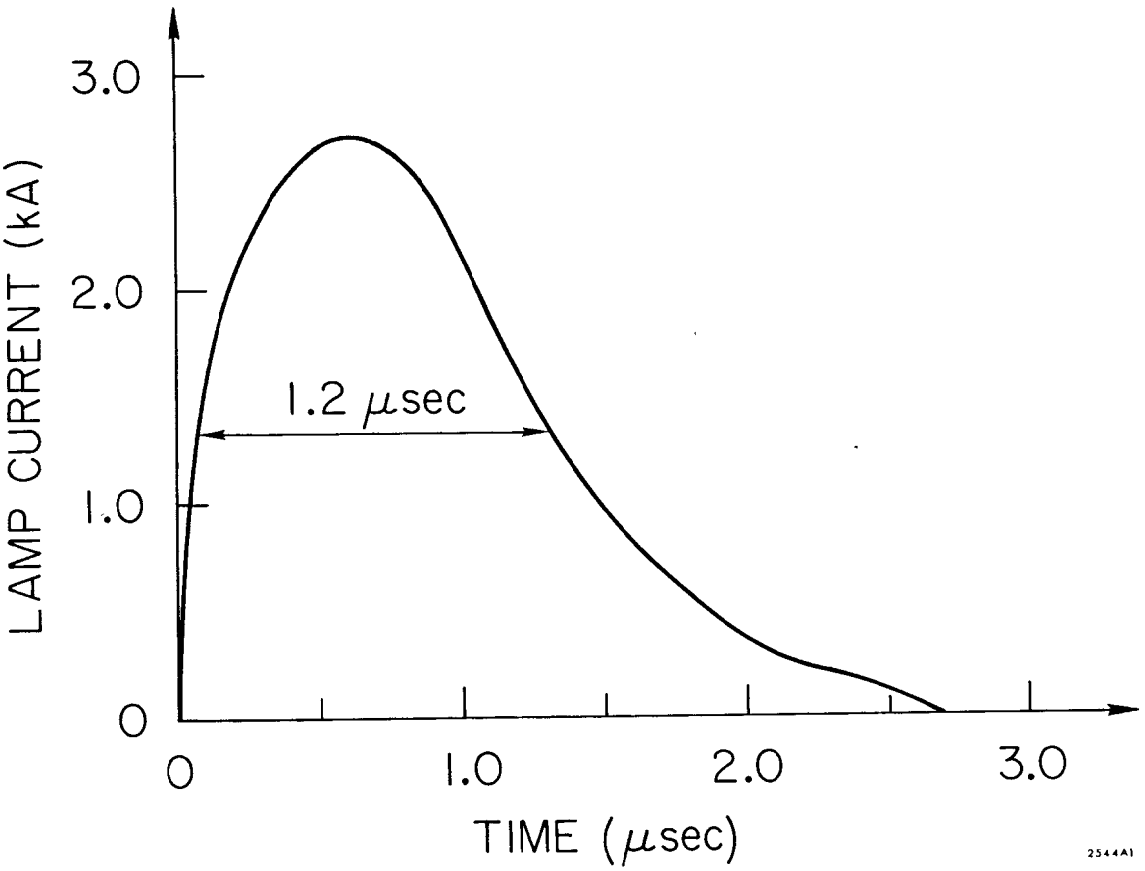


Fig. 4

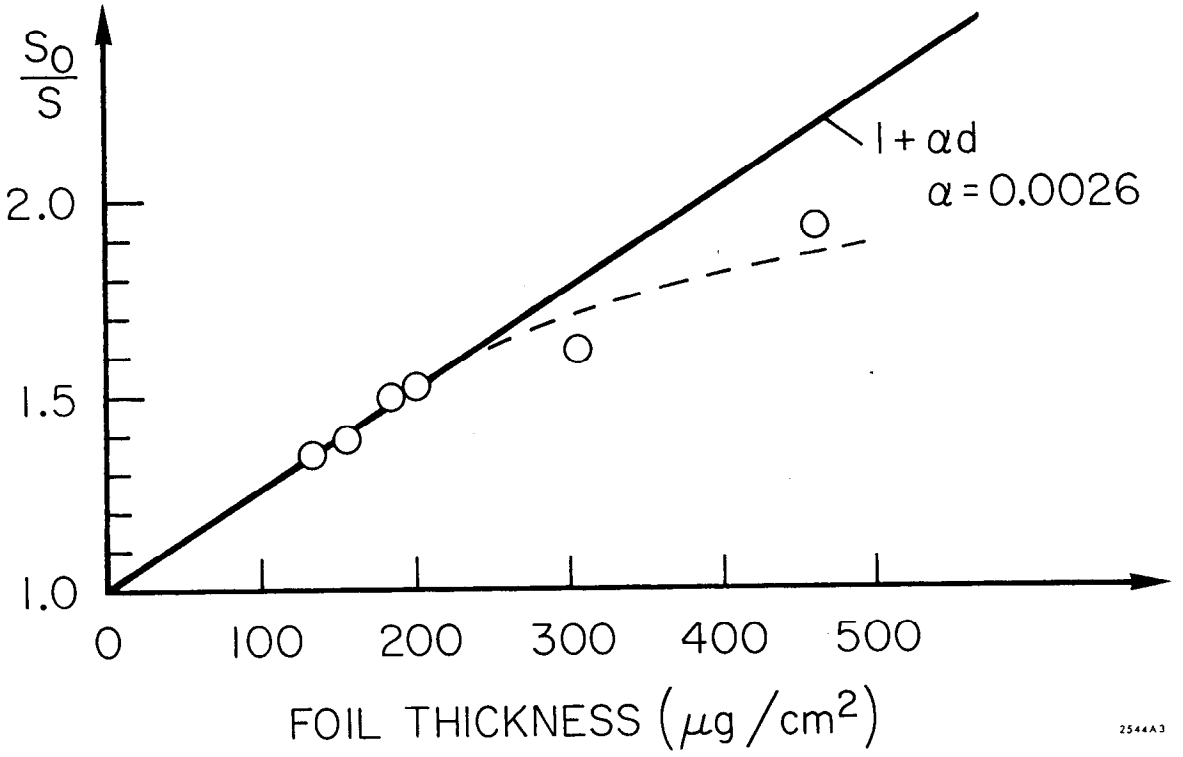

$\frac{S_0}{S}$
2.0
1.5
1.0
0
100
200
300
400
500
$1+\alpha d$
$\alpha = 0.0026$
FOIL THICKNESS ($\mu g/cm^2$)
2544A3

Fig. 5