DEVELOPMENT OF AN OPTICAL DISC RECORDER

QUARTERLY TECHNICAL REPORT

1 April 1976 to 30 June 1976

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY

ARPA Order No. 3080
Program Code No. 6D30

Contract No. N00014-76-C-0441

Principal Investigator:	George Kenney (914) 762-0300
Scientific Officer:	Marvin Denicoff
Amount of Contract:	$700,719
Contract Period:	1 Oct. 1975 - 31 March 1977

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

Prepared by

PHILIPS LABORATORIES
A Division of North American Philips Corporation
Briarcliff Manor, New York 10510

August 1976

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
6 DEVELOPMENT OF AN OPTICAL DISC RECORDER.

5. TYPE OF REPORT & PERIOD COVERED
9 Quarterly Technical Report.
1 Apr[redacted] - 30 Jun[redacted]76

6. PERFORMING ORG. REPORT NUMBER
14 PL-21-YR76-0815

7. AUTHOR(s)
10 George Kenney, D. Lou, J. Wagner, A. Chan
T. Demetrakopoulos, R. McFarlane, P. Janssen

8. CONTRACT OR GRANT NUMBER(s)
15 N00014-76-C-0441,
ARPA Order-3080

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Philips Laboratories
A Division of North American Philips Corp.
Briarcliff Manor, New York 10510

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
ARPA Order No. 3080
Program Code No. 6D30

11. CONTROLLING OFFICE NAME AND ADDRESS
Advanced Research Projects Agency
1400 Wilson Blvd.
Arlington, Virginia 22209

12. REPORT DATE
11 August 1976

13. NUMBER OF PAGES
50

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217
Code: 437
12 50p.

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release. Distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

optical disc recorder	recording materials
direct read after write (DRAW)	disc protective mechanism
lasers	disc
substrate materials	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

First testing of the recorder is underway. Some tracks were recorded on plastic discs coated with tellurium films. Laser machining of holes in static films of various materials reveals tellurium as an attractive DRAW candidate. The principle advantages of tellurium film (compared to bismuth) are improved sensitivity and stability at high temperature. Detailed analysis of the air-sandwich protective mechanism continues. The first results of the digital coding task force study are being analyzed. A study of accelerated life testing of bismuth and tellurium film was initiated.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED 387 334

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

TABLE OF CONTENTS

Section Page

Appendix

PHILIPS LABORATORIES

QUARTERLY TECHNICAL REPORT
1 April 1976 to 30 June 1976

1. SUMMARY

First testing of the recorder is underway. Some tracks were recorded on plastic discs coated with tellurium films. Laser machining of holes in static films of various materials reveals tellurium as an attractive DRAW candidate. The principle advantages of tellurium film (compared to bismuth) are improved sensitivity and stability at high temperature. Detailed analysis of the air-sandwich protective mechanism continues. The first results of the digital coding task force study are being analyzed. A study of accelerated life testing of bismuth and tellurium film was initiated.

2. RESEARCH PROGRAM OBJECTIVES

The objective of this program is to develop an optical disc recorder of digital information, with a direct-read-after-write (DRAW) capability. A storage capacity of $> 10^{10}$ bits is desired, with 4.4×10^5 bits on each of the 40,000 tracks of the disc. The desired error rate is 10^{-9} at a data rate greater than 1.33 M bit/sec. The key element in the proposed system is a recording material that can be exposed with a low-power laser (e.g., HeNe) - leading to a recorder which could be manufactured for < $10,000 and discs which would cost < $10 in quantity.

3. SCHEDULE

The program schedule and milestones given in Figure 1 are for both materials development and recorder construction. The first narrowing of material choice (Milestone 1) was completed with tellurium and bismuth films as the first and second choices. Milestone 2 (large-area film deposition) has also been met but the quality of deposition must still be tested by recording full discs. The results of full disc recording tests is expected to allow further narrowing of the material choice by October 1976. The dynamic testing includes measurements of signal-to-noise ratios

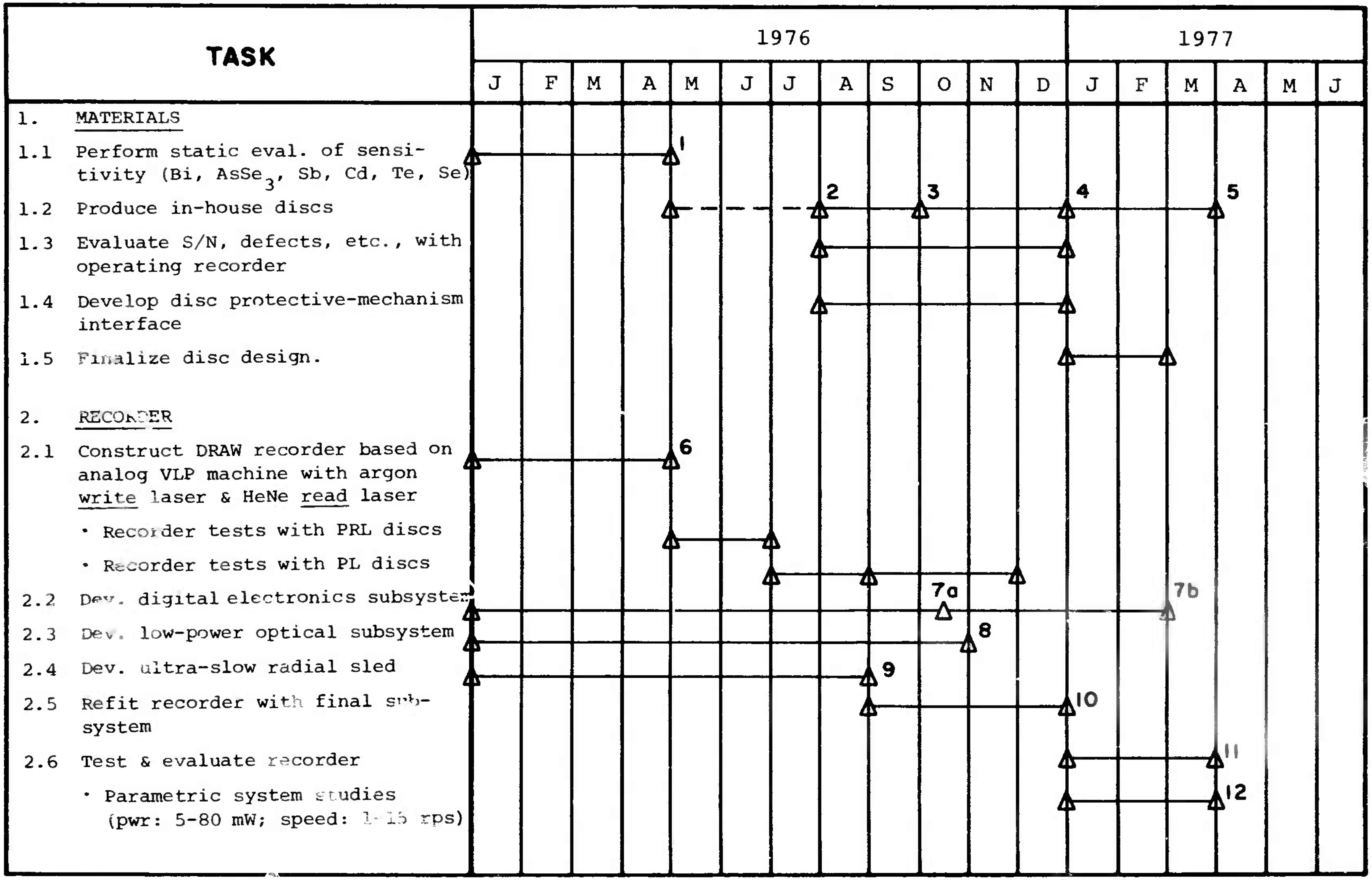


Figure 1: Program Schedule for Development of Optical Disc Recorder (sht. 1 of 2)

TASK	1976												1977					
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J

PROGRAM MILESTONES

Milestone No.	Description
1	First narrowing of material choices complete.
2	large-area deposition capability available.
3	Second narrowing of material choices complete.
4	Optimum material selected.
5	Deliverable discs available.
6	Recorder available for test.
7a	Characterization of recorder channel complete.
7b	Assy. of digital electronics subsystem complete.
8	Assy. of optical subsystem complete.
9	Assy. of improved radial sled complete.
10	Final system assembly and checkout complete.
11	Deliver laboratory prototype system.
12	Parametric system studies completed.

Figure 1: Program Schedule for Development of Optical Disc Recorder (sht. 2 of 2)

and defects; this testing requires an operational recorder as a test vehicle. The results of the dynamic testing and the materials deve-opment phase should allow a final material selection by January 1, 1977. During the material development phase, uniform deposition techniques for large areas will be investigated, and special consideration will be given to any interaction between those techniques and the protective mechanism (i.e., air sandwich) for the disc.

Construction of the recorder (Milestone 6) was accomplished and the tests with plastic discs were initiated. Problems with the travel range of the focusing system prevented complete testing. The focusing system is being reworked and the recorder should be ready by August 1976.

The completion of the digital electronics (Milestone 7b) has been rescheduled to February 1977; the digital electronics are not required for anticipated work in 1976. Furthermore, the effectiveness of the encoding and decoding error correction schemes will be greatly improved by awaiting full characterization of the recording channel. The recording channel characterization is being done by PRL* and initial results should be available by October 1976 (7a).

Various designs of a low powered optical subsystem have been considered. The final choice has been delayed (60 days), completion of the optical subsystem design (Milestone 8) rescheduled to the end of October, by the focusing system rework. The development of an ultra-slow radial sled (Milestone 9) was completed ahead of schedule.

4. PROGRESS AND DISCUSSION

The individual subsystems of the recorder was dynamically tested on the assembled recorder and rendered operational. The focus servo was found to have a range of ± 200 μm which was extended by modification to ± 0.5 mm. The design goal, a function of the

---

* Philips Research Laboratories, Eindhoven, Netherlands.

disc unflatness, is ± 1 mm. The blue record optical subsystem was tested for transmission efficiency and diffraction limitations. The first system was designed for a transmission of at least 35%. The measured transmission was 40% primarily due to losses with the recording objective lens. A specially designed objective lens, with improved efficiency of 60%, will be ordered in a few months. Therefore, with a 20 mW laser we can expect at least 8 mW and possibly 12 mW focused at the disc's surface and usable for hole machining. Further improvements in the transmission efficiency can be expected with better light modulators. The present system employs an electro-optic modulator with 75% transmission. Several manufacturers of acousto-optic light modulators are able to supply modulators with 90% efficiencies. An acousto-optic modulator will be included with prototype because of the higher optical transmission efficiency and lower cost.

The air bearing sled was measured at extremely slow speed and found to have uniform speed down to 2.8 μm/sec. Appendix I is a description of the velocity measurement technique and the detailed results. Uniform sled motion at 4.5 μm/sec is critical to the concept of an inexpensive recorder using a low powered laser. These first tests indicated that sled-motion uniformity satisfies the design goals.

To illustrate the importance of the minimum sled speed requirement, consider for example the case where the minimum uniform sled speed is 9 μm/sec. To maintain 2.0 μm track spacing the disc must now rotate at twice the old design speed for 6 rps. This faster disc speed will allow a higher data rate but only if more laser power is available for recording. For this reason the design parameters of 20 mW laser, 3 rps disc speed, 2 μ track spacing, and a sled speed of 4.5 μm/sec are closely coupled.

Preliminary measurements of the first PRL air bearing turntables indicate that average spindle wobble without a disc is 0.28 μm at 0.15 rps. Wobble was interpreted to be the irregularity in cyclic run-out of the spindle surface. The run-out was measured with a non-contacting displacement transducer. Two additional air bearing turntables were supplied by PRL. The units are much smaller than the present turntable and will be incorporated into the recorder. Dover Inc., Waltham, Mass. can also supply an air bearing turntable with 0.2 μm wobble. The design goal for wobble is 0.1 to 0.2 μm.

Progress has been made toward achieving Milestone 5 in the matter of disc/protective mechanism construction. A fixture for assemblying air sandwich discs was designed and will be fabricated shortly. The primary purpose of the fixture is to insure that the substrates remain flat during assembly and that all of the individual disc elements (substrates and stand offs) are aligned in a concentric fashion. The principle involved is to mount the substrates on vacuum hold-down plates and then mate them with a common locating spindle.

PL will also examine the best way of achieving a uniform adhesive line in the air sandwich. In addition to uniform curing pressure, it is important to be able to deposit a uniform distribution of adhesive prior to assembly.

An experimental air sandwich was made and will be tested for radial and transverse deformations at 1800 rpm. The results will then be compared with the theoretical predictions, as reported in the previous quarterly report.

Static sensitivities of four candidate materials (bismuth, arsenic selenide, selenium and tellurium) were characterized in some detail for the argon laser wavelength 488 nm. Although the tests used 488 λ light the results should apply equally well at 6328 λ for bismuth and tellurium as both metals have uniform absorption over the visible band. Selected results and experimental methods are presented in Appendix II. The figures show machined holes vs. film mass thickness for various incident powers. For exposure times greater than 100 ns, the films exhibit a peak sensitivity at an optimum mass thickness. This can be attributed to two opposing mechanisms; very thin films are not absorbing sufficiently and lose heat to the substrate, while very thick films have more mass per area and consequently require more power for hole chining. Under optimum conditions, the laser powers required to produce one micron diameter pits are listed in Table 1.

Bismuth and tellurium are absorbing for wavelengths out into the near infrared, while selenium and arsenic selenide are not absorbing at HeNe wave lengths, and are attractive only for blue and ultraviolet recording.

Table 1: Laser power required to produce one micron diameter pits under optimum conditions.

Material	100 nsec exposure 10 Mbits/sec	500 nsec exposure 2 Mbits/sec
Bi	14 mW	7 mW
$AsSe_3$	12 mW	3 mW
Se	12 mW	2 mW
Te	7 mW	4 mW

A theoretical analysis was performed which shows that, under optimum operating conditions, the dynamic sensitivities on a moving substrate scales linearly with the pit size produced. (The analysis will be formalized and presented in the next quarterly report.) For the proposed digital recorder, where 2 μm x 1 μm pits would be used on the outer edge of the disc, the required laser power will be approximately double those listed in Table 1. The principle advantages of tellurium films (compared to bismuth) are improved sensitivity and stability at high temperature. Using a low-cost 20 mW HeNe laser, under various levels of systems optimization, the maximum uncorrected data rates of 2 Mbit/sec for bismuth and 5 Mbit/sec for tellurium can be expected.

Harris Inc. and Interaction Inc., both manufacturers of light modulators, are presently conducting a study to determine the trade-off of price, bit rate, transmission, and other performance parameters for acousto-optic devices. It may well be that tellurium will allow a 5 Mbit/sec data rate, but system-cost constraints may limit the modulation frequency to 2 Mbit/sec.

Discs of these materials have been fabricated with a thickness uniformity of ± 3%. Test results show that 5 to 10% will be acceptable. Using the present recording optics, 1 μm holes were machined in tellurium films on a rotating plexiglas disc (see Fig. 2). The conditions for recording were similar to those for video recording, viz., disc speed 30 rps, sled speed 45 m/sec, recording wavelength 4880 Å, exposure time 50 ns. Since the playback optics are not yet operational, we have nc indication of the overall recording quality except from the pit photographs (Fig. 2). Judging from the photograph, the signal-to-noise ratio should be more than sufficient for recording digital information. Tests in the DRAW mode will be made to confirm that the pit quality is acceptable.

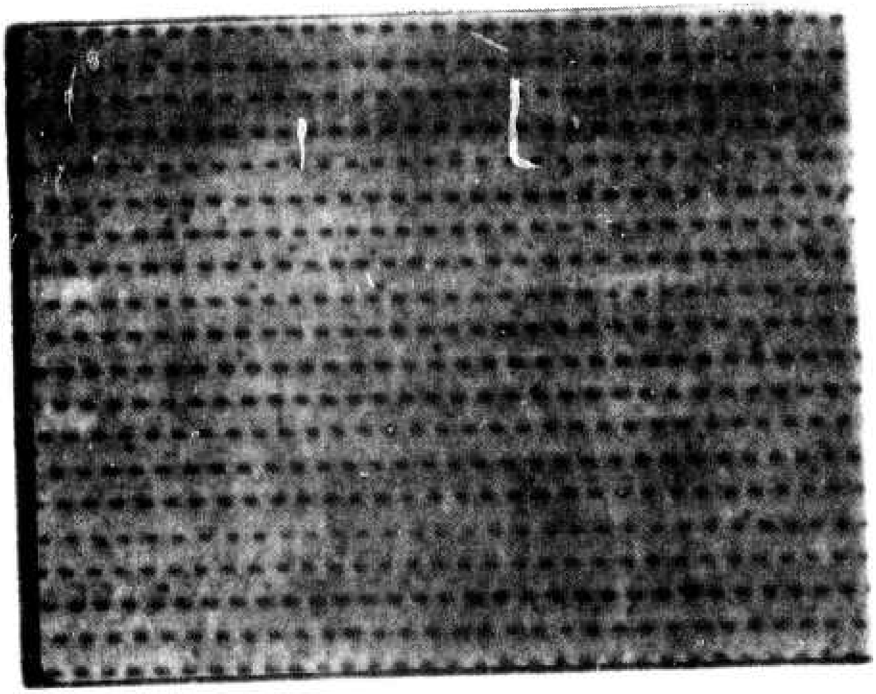


Figure 2: Holes machined in tellurium films on plexiglas disc. Exposure time 50 ns, track spacing 2μ, hole width 4μ.

A task force to study digital coding problems met at PL on May 19 and 20, 1976. The committee includes members from PRL and two divisions of Magnavox. A first look at the digital recording channel of bismuth master discs was presented. The important parameters measured were the frequency and type of dropouts seen, the average distance between dropouts, and the average size of the dropouts. The first data was insufficient to accurately characterize the channel due to contamination of the disc by dust and inadequate measurements. PRL agreed to supply further information necessary for channel characterization. Magnavox and PRL will study the channel characteristics and recommend the best error correction coding approach. In September, Magnavox will present a plan to PL for coding hardware development. Testing of the decoder is scheduled for February 1977 at Philips Laboratories. Of particular interest is a trade-off comparison of decoder cost vs. data rates. Our present goal is for a maximum raw data rate of 2 Mbit/sec with a usable data rate of 1 Mbit/sec (overall rate 1/2 code). Magnavox will also study data format and buffer sizes required for practical error correction and D.C. restoration techniques. Of special interest is the program for handling "uncorrectable" errors. The next meeting is tentatively set for September 21-22, 1976 at Philips Laboratories.

A study of accelerated life testing of bismuth and tellurium films has been initiated in anticipation of faborable action on PL Proposal No. 40576.

5. PLANS FOR NEXT QUARTER (Refer to Section 3 for details).

a. Finish the design of the recording optical subsystem for a HeNe (red) laser with high efficiency.
b. Render the present playback optical system operational.
c. Begin dynamic testing of Te and Bi coated discs.
d. Conduct life testing of Te and Bi films.
e. Conduct first tests of recording in the air sandwich configuration.
f. Evaluate digital recording channel characteristics.

APPENDIX I

SPEED MEASUREMENTS - DOVER AIR BEARING SLED

SPEED MEASUREMENTS - DOVER AIR BEARING SLED

by

John G. Wagner

The following memorandum is a detailed description of the speed measurements which L. Irizarry, F. Nielsen and I have made on the Dover Air Bearing sled. The results indicate that the sled can be driven at preselected speeds ranging from 2.8 to 580 micrometers per second. At the lowest speed setting (0.0) on the controller, the speed varied in a smooth cyclic fashion between ± 6% of the average value. The period of variation was about 3 1/2 minutes. At some of the highest speed control settings, continuous variations of ± 3% occurred about every second.

TEST SET-UP

Figure 1 shows a schematic of the test set-up. A non-contracting displacement transducer was used to measure the position of the optical tray. The probe axis of the transducer was set parallel to the line of travel of the bearing and passed through the geometric center of the end view of the tray base. The transducer used was a Bently Nevada 3000 Series Proximitor (Probe #190-00-00-07-30-02 and Driver #3106). The probe was fixed to a micrometer positioner and calibrated in place. The calibration factor of 0.1 micron gap change per millivolt of output was constant for gap widths up to 1 millimeter. By repositioning the probe, speed measurements for total sled displacements of up to 1 centimeter were made. Transducer output was recorded versus time on either a Hewlett-Packard Strip Chart Recorder 7100 BM or Tektronix 475 Oscilloscope depending on the sleed speed. Sled speed was determined by differentiating the signal. The frequency response of the Proximitor is 0 to 10,000 Hz. Line pressure for the bearing was maintained at 70 psig. All measurements were made with the bearing bace centrally located between stops.

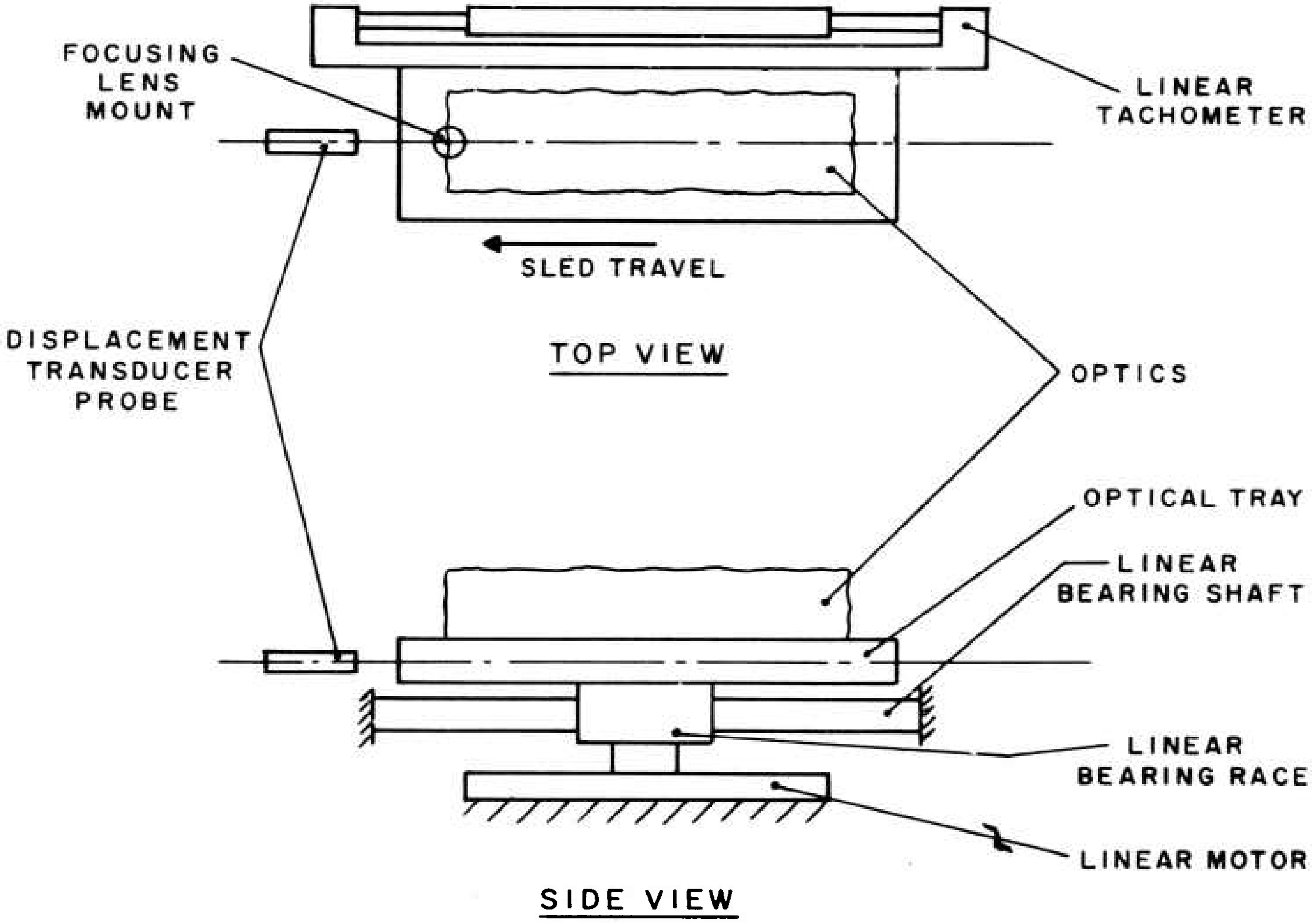


Figure 1: Sled Test Configuration.

RESULTS

The overall speed calibration is shown in Figure 2. For plotting purposes the measurements have been broken into two sets. One set corresponding to sled speed control settings ranging from 0.0 and the other set corresponding to settings ranging from 1 to 10. Table 1 provides the average speeds (shown as dots in Figure 1) and the number of measurements that went into calibrating the average for various settings of the Sled Speed Control. For future reference the corresponding voltage, measured at the non-inverting input to integrated circuit 741 on the linear motor servo card of the controller, has been listed in the right hand column.

A check was made on the noise levels associated with the individual measurements. The tray position was monitored versus time using the A.C. amplifier input on the oscilloscope. By this technique only the high frequency content of the tray position was recorded. Four tests were conducted using this method: (a) air flow off, motor drive off; (b) air flow on, motor drive off; (c) air flow on, Sled Speed Control setting 1.0; (d) air flow on, Sled Speed Control setting 0.0. The results are shown in Figure 3. In all four cases the vertical gain is 0.2 micron gap change per division and the inverse sweep speed is 10 milliseconds per division. The recordings indicate that the uncertainty in tray position due to seismic like activity of the table is about .08 micron (Fig. 3a). The noise with air flow through the bearing (Fig. 3b) is about .12 micron. The worst case in the driven mode seems to be at the slow speed where the uncertainty is at most .16 micron. Checks were made to assure that the vibrational motion measured was that of the optical tray and not the probe.

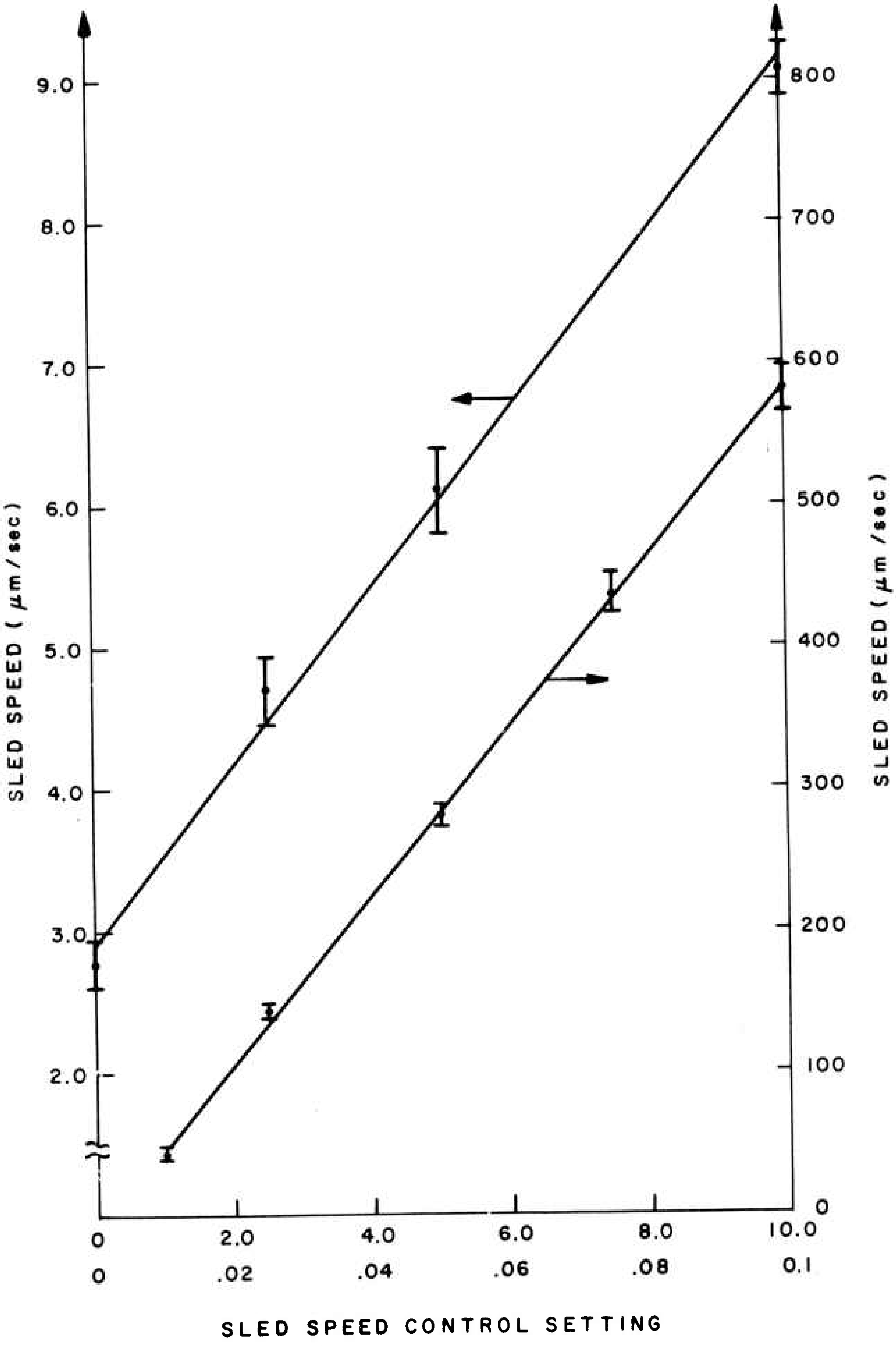
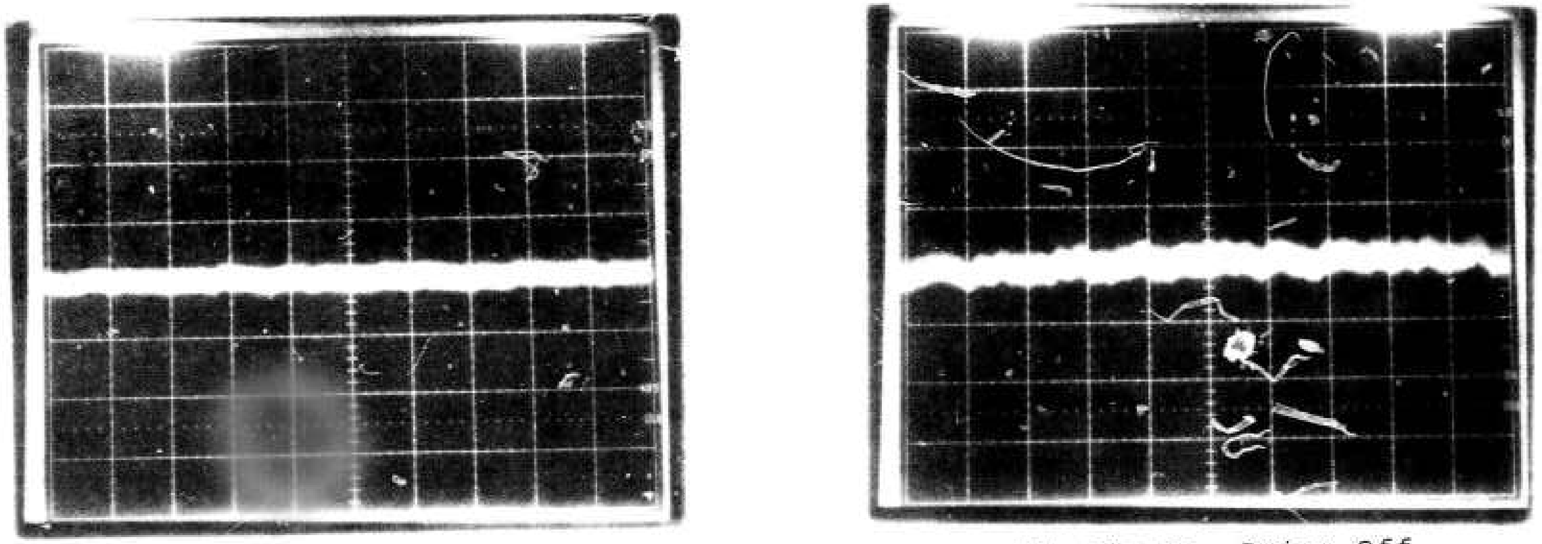


Figure 2: Sled Speed Calibration.

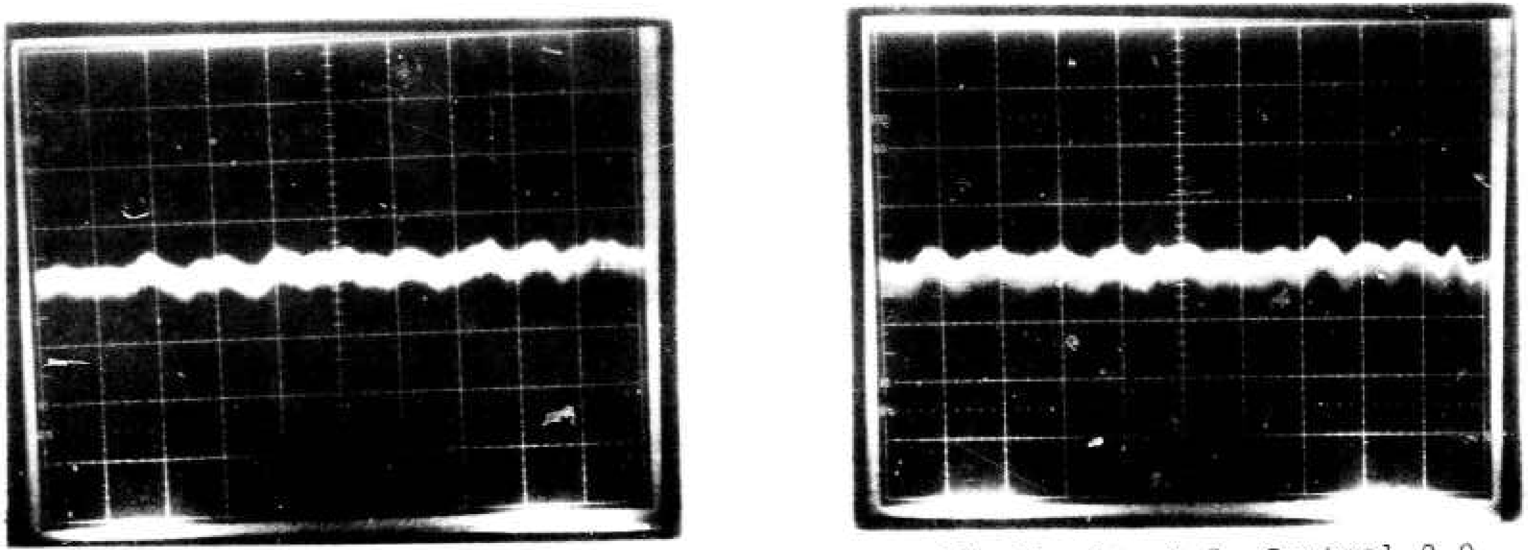
TABLE 1

Sled Speed Control Setting	Speed (μm/sec)	Voltage (Mv)
10.0	580 (2)	431.0
7.5	438 (5)	324.25
5.0	280 (2)	217.25
2.5	140 (3)	109.95
1.0	44 (4)	43.82
0.1	9.1 (4)	5.18
0.05	6.1 (2)	3.05
0.025	4.7 (5)	2.01
0.0	2.8 (26)	.895



(a) Air Off, Drive Off

(b) Air On, Drive Off



(c) Air On, S.S. Control 1.0

(d) Air On, S.S. Control 0.0

Figure 3: Noise Measurements.

APPENDIX II

CHARACTERIZATION OF THE STATIC LASER MACHINING SENSITIVITIES OF THIN FILMS OF BISMUTH, SELENIUM, TELLURIUM AND ARSENIC SELENIDE

CHARACTERIZATION OF THE STATIC LASER MACHINING SENSITIVITIES OF THIN FILMS OF BISMUTH, SELENIUM, TELLURIUM AND ARSENIC SELENIDE

David Lou
Marian Strzelczyk
Pedro Tasaico

I. INTRODUCTION

This memorandum summarizes experimental results on the static sensitivities to laser machining of thin films of bismuth (Bi), selenium, (Se), tellurium (Te) and arsenic selenide (AsSe).

II. EXPERIMENTAL METHODS

A. Sample Preparation

The measurements are done on substrates of PMMA (polymethyl methacrylate) and glass. The standard cleaning procedure for PMMA is listed below.

(1) Ultrasonic cleaning in acetone 15 sec.
(2) Rinse with Methyl alcohol.
(3) Rinse with distilled water.
(4) Ultrasonic cleaning in detergent (alkanox) solution.
(5) Rinse in distilled water.
(6) Ultrasonic cleaning in distilled water.
(7) Blow dry with nitrogen.

For glass samples, steps (1) to (3) are omitted.

Films are deposited by vacuum evaporation. The typical background pressure was 2×10^{-6} torr. Typical deposition conditions are shown in Table I. Mass thicknesses were determined from quartz crystal monitor measurements. These thicknesses were then calibrated against actual thicknesses measured on the samples by means of a Varian Å scope. The results of these calibrations are shown in Fig. 1. Their consistency indicates a reasonable validity for the thickness measurements.

B. Sensitivity Measurement

Figure 2 shows a schematic of the sensitivity measurement apparatus. The beam from an argon laser lasing at 488 nm is modulated by means of an electroptic modulator to produce pulses of duration from 50 nsec to 1.0 μsec. The power level and extinction ratio of the modulated beam is monitored by splitting off part of the beam into a photodiode detector. The beam is then attenuated to the proper power level by inserting an attenuator into the beam path. It is then focussed through a spot lens to completely overfill a numerical aperture 0.75 microscope objective. The power level incident onto the sample is measured by collecting the output of the unmodulated laser beam through the microscope objective onto a power meter. The sample is mounted on a rotating substrate holder which rotates past the microscope objective at a slight angle of tilt. The rotational velocity is such that the sample can be considered to be stationary relative to the laser beam. Focussing onto the sample is obtained by observing the back reflection from the sample on a screen. The tilt angle is adjusted so that as the sample is rotated through the beam, it intersects the beam at various distances from the focal point. The effective diameter of the laser beam incident onto the sample therefore varies according to the angular position along the track. As the sample is rotated through the beam, a track of holes is produced. The diameters of these holes vary as a function of their distances along the track. Maximum hole size is obtained when the effective diameter of the laser beam is optimum for producing that size hole. These are the hole sizes measured for sensitivity. The hole sizes are measured by optical microscopy. The results for glass substrates are checked against measurements obtained by scanning electron microscopy and found to be in good agreement.

III. RESULTS

The results for bismuth are shown in Fig. 3 for various pulse exposure durations. Here we have plotted the diameter squared of the holes formed by laser machining as a function of the power level at the surface of the film and film thicknesses. Figures 4, 5 and 6 show the same results for selenium, tellurium and arsenic selenide respectively. Several general comments may be made.

(1) For short pulse exposure durations (≈100 nsec) where the laser machining process is essentially adiabatic, the sensitivities for glass and PMMA substrates are comparable. For longer pulse exposure durations (≈500 nsec), where heat loss to the substrate becomes important, the sensitivities on glass are substantially worse than on PMMA.

(2) In general, for different pulse exposure durations and different materials there exist different optimum thicknesses to produce the maximum hole size. The differences can be attributed to changes in optical absorption, thermal relaxation time and film structure as the thicknesses are varied. The optimum thicknesses are listed in Table II.

(3) The amount of laser power at 488 nm required to produce 1μm diameter holes are listed in Table III for the various materials and pulse exposure durations. It can readily be seen that with 1 mW delivered to the surface of the film, all four materials can be used to produce recordings at 2 Mbits/sec

(500 nsec exposure duration). Selenium and arsenic selenide are sensitive only in the blue, while tellurium and bismuth can be used with a red He-Ne laser.

TABLE I.

TYPICAL DEPOSITION CONDITIONS

	STARTING MATERIAL	DEPOSITION RATE (Å/sec)	EVAPORATION SOURCE
Se	5-9's In lab materials	30	$A\ell_2O_3$ crucible W filament
Te	5-9's Apache Chemicals	10	W boat
Bi	5-9's In lab materials	10	$A\ell_2O_3$ crucible W filament
$AsSe_3$	20 at % As (5-9's In lab materials) 80 at % Se (5-9's In lab materials) Heated overnight in Argon atmosphere at 450°C and quenched	15	Quartz crucible W filament

TABLE II

OPTIMUM FILM THICKNESSES FOR MAXIMUM SENSITIVITY TO LASER MICROMACHINING ON PMMA SUBSTRATE

	Exposure Duration	
	100 nsec	500 nsec
Bismuth	300Å	500Å
Selenium	800Å	800Å
Tellurium	100Å	400Å
Arsenic Selenide	800Å	800Å

TABLE III

LASER POWER AT 488 nm REQUIRED TO PRODUCE 1μm DIAMETER HOLE ON PMMA SUBSTRATE

	Exposure Duration		
	100 nsec	500 nsec	750 nsec
Bismuth	14 mW	7.0 mW	6.0 mW
Selenium	12 mW	2.0 mW	2.0 mW
Tellurium	7 mW	4.0 mW	3.0 mW
Arsenic Selenide	12 mW	3.0 mW	3.0 mW

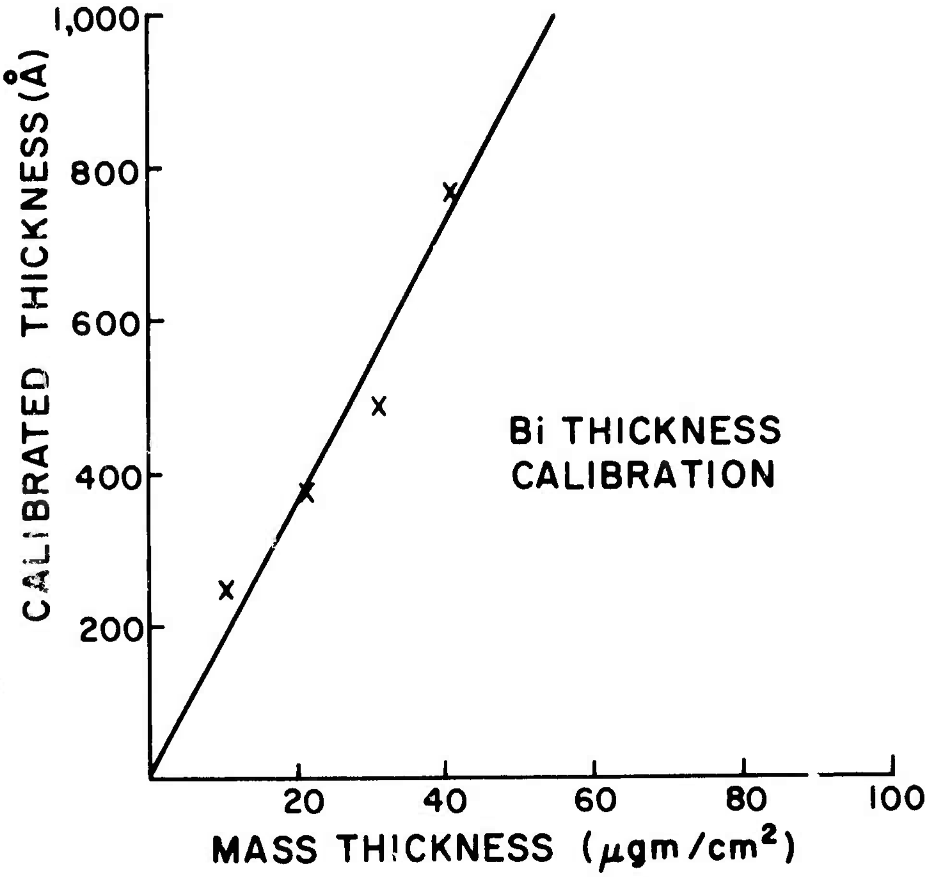


Figure 1a: Thickness calibration for bismuth.

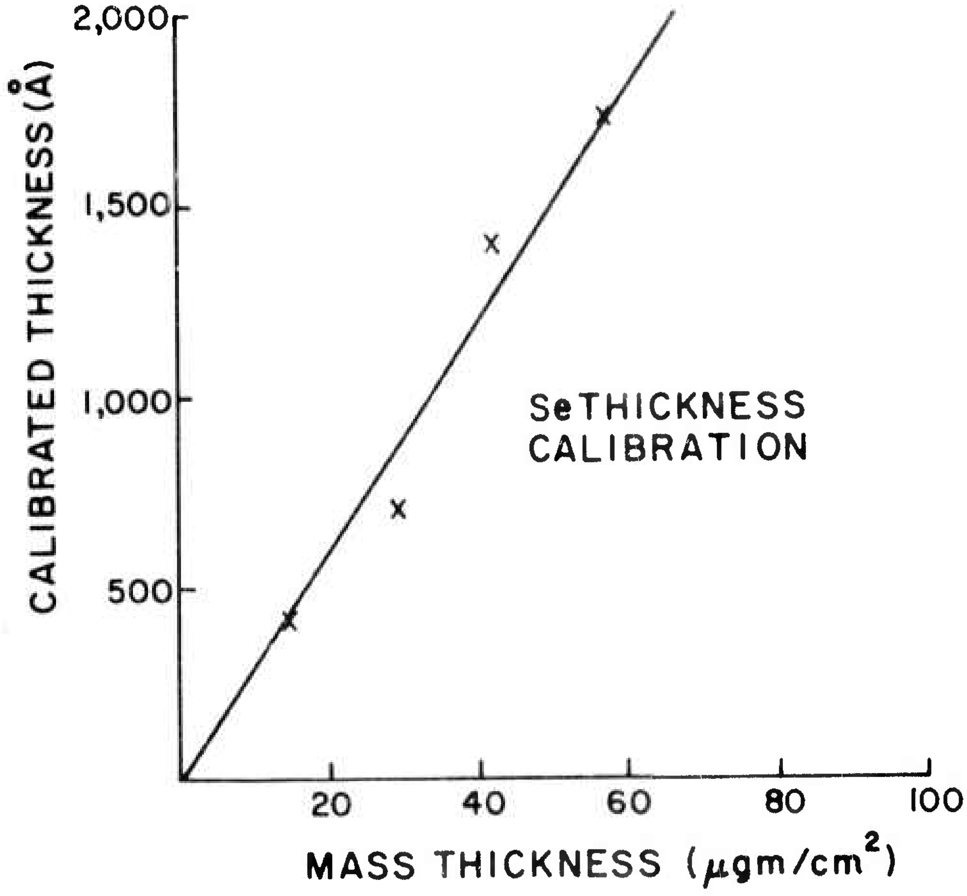


Figure 1b: Thickness calibration for selenium.

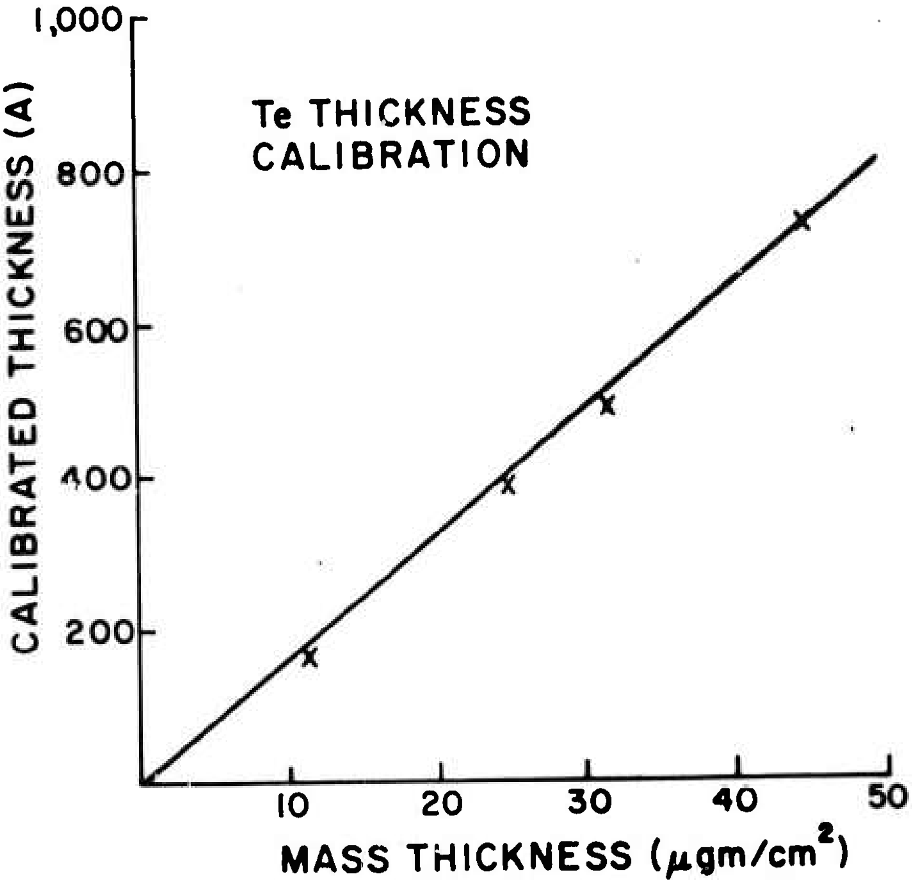


Figure 1c: Thickness calibration for tellurium.

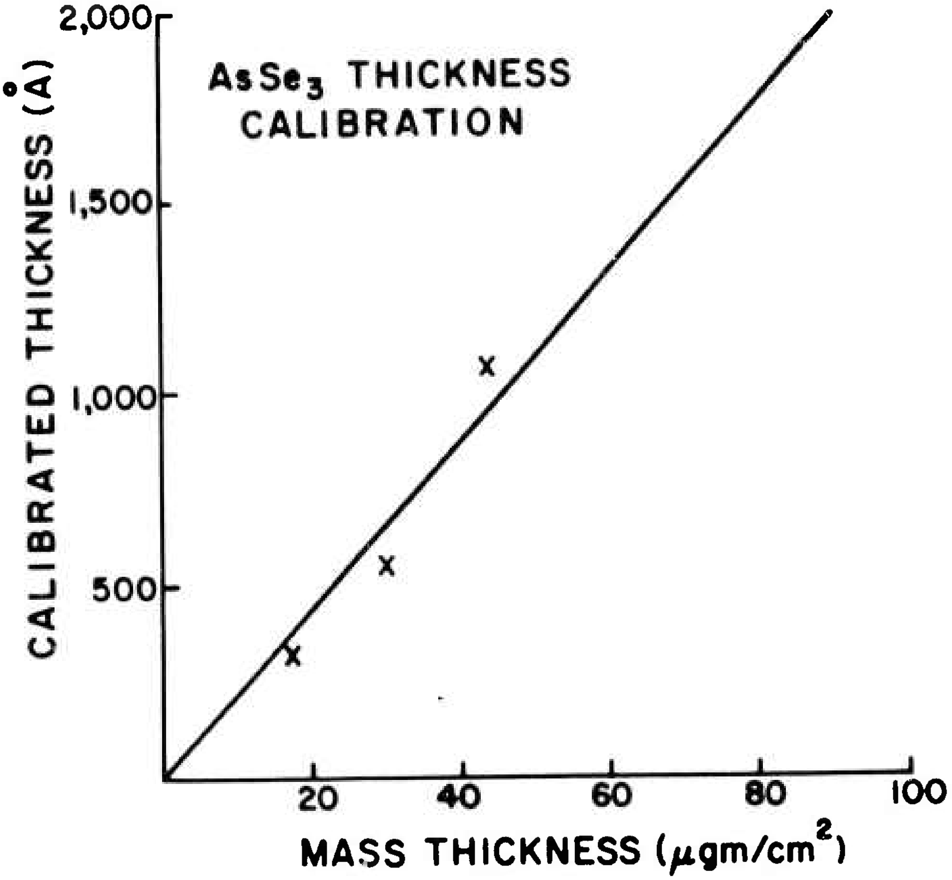


Figure 1d: Thickness calibration for arsenic selenide.

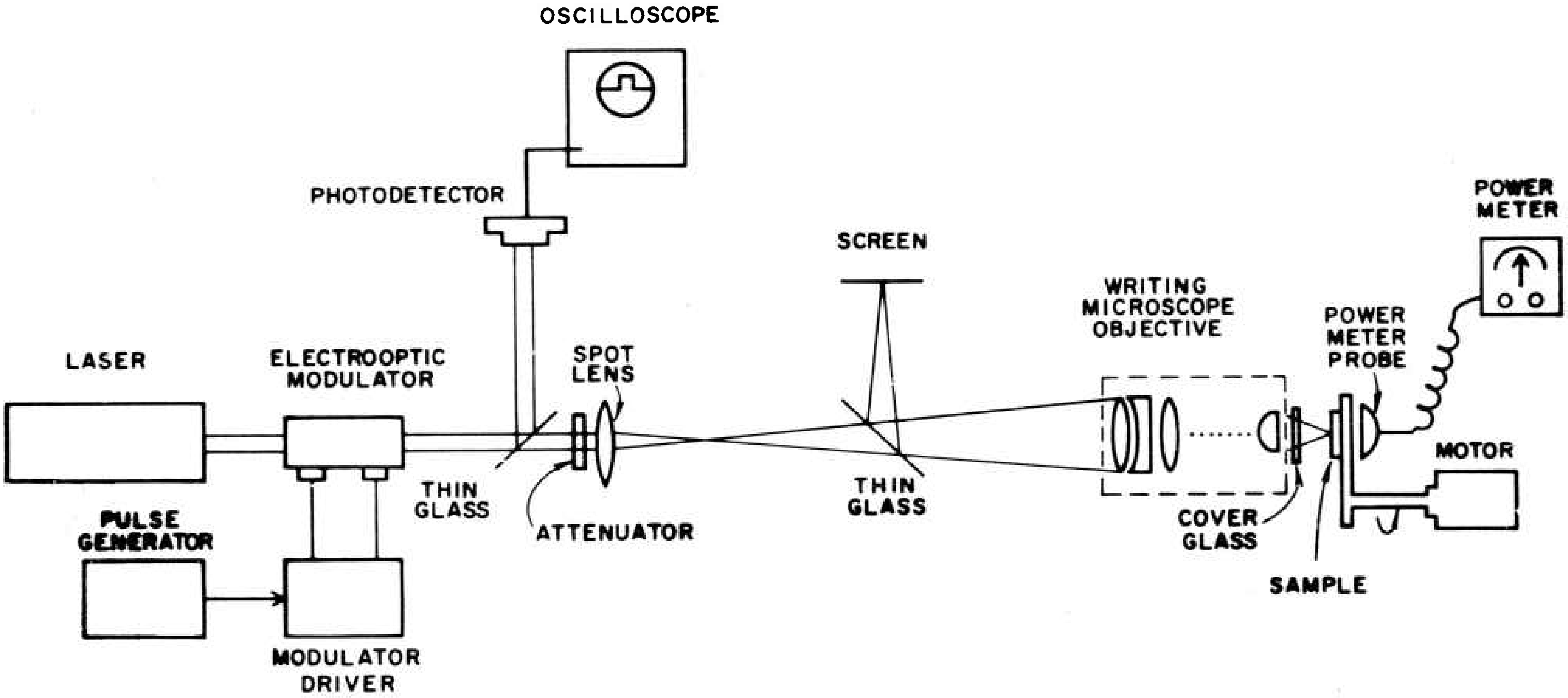


Figure 2: Schematic of the apparatus for sensitivity measurement.

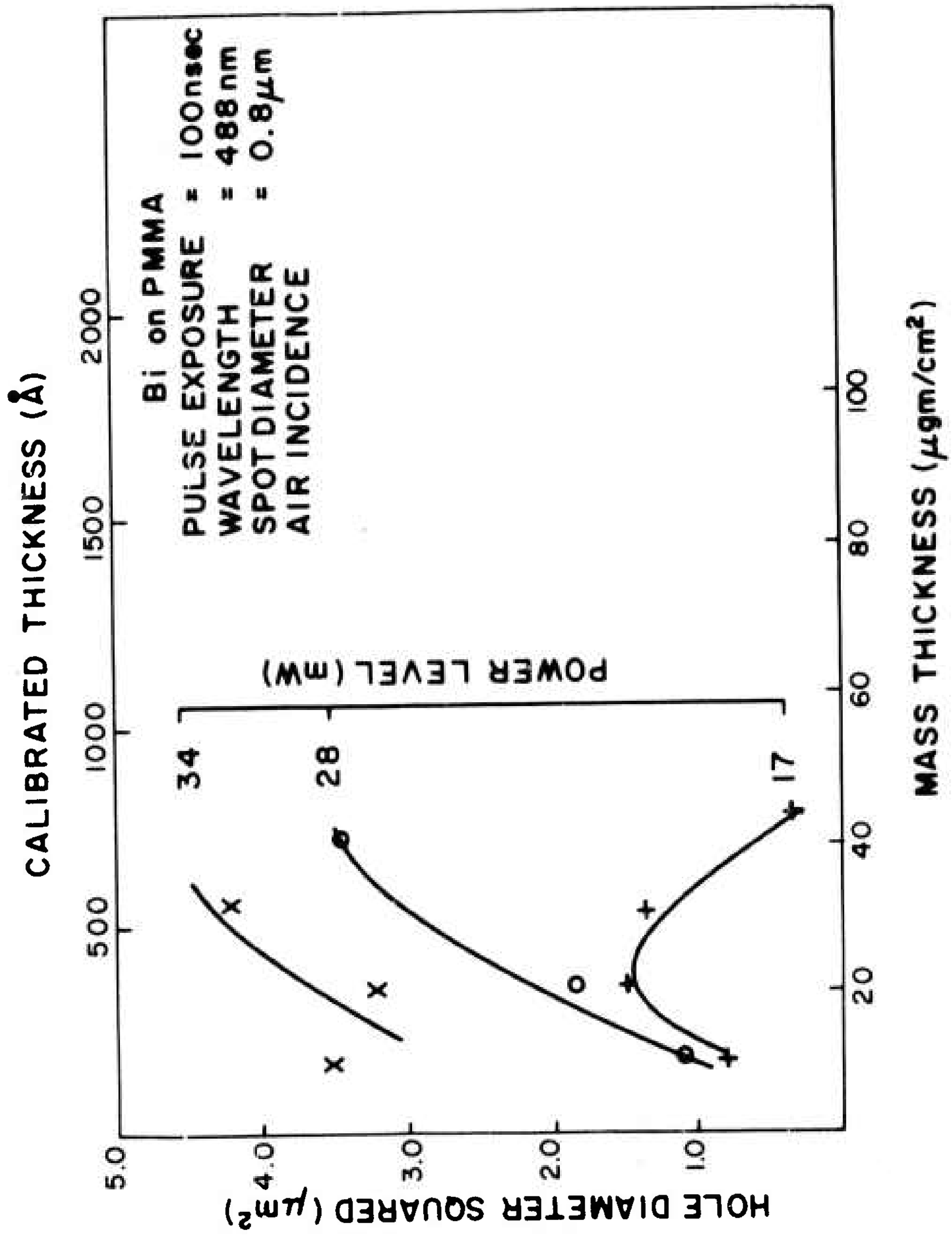


Figure 3a: Sensitivity for bismuth films to laser micromachining.

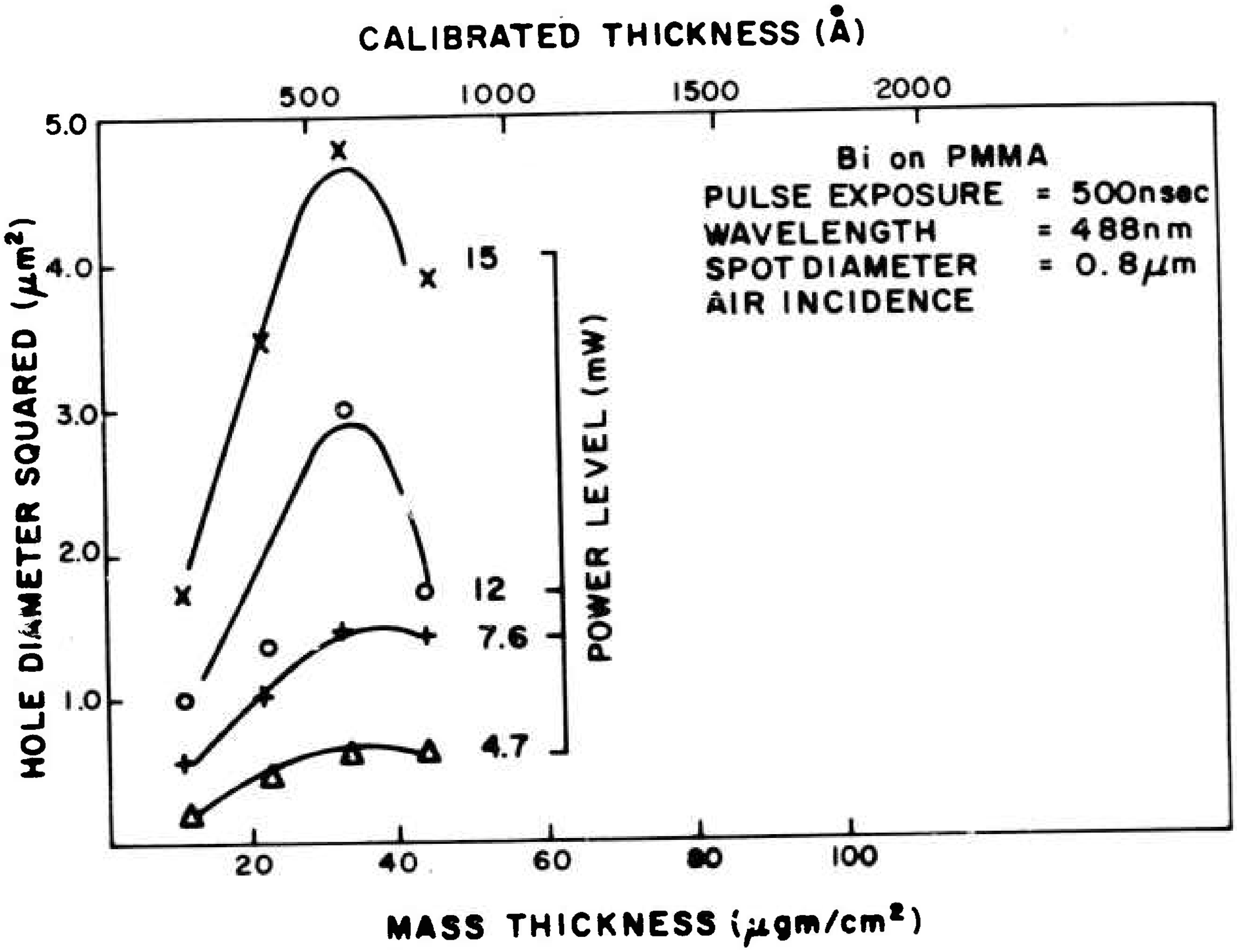


Figure 3b: Sensitivity for bismuth films to laser micromachining.

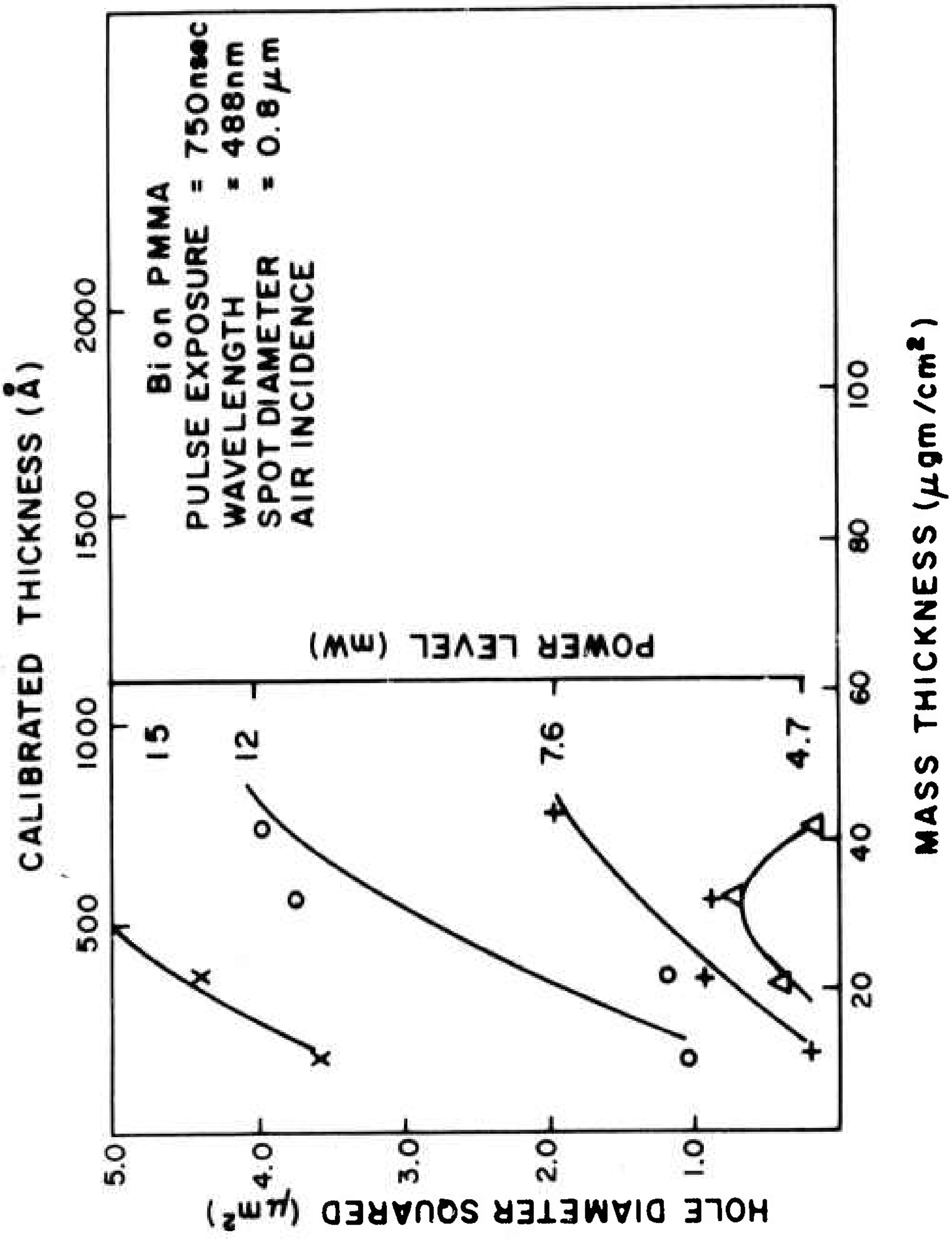


Figure 3c: Sensitivity for bismuth films to laser micromachining.

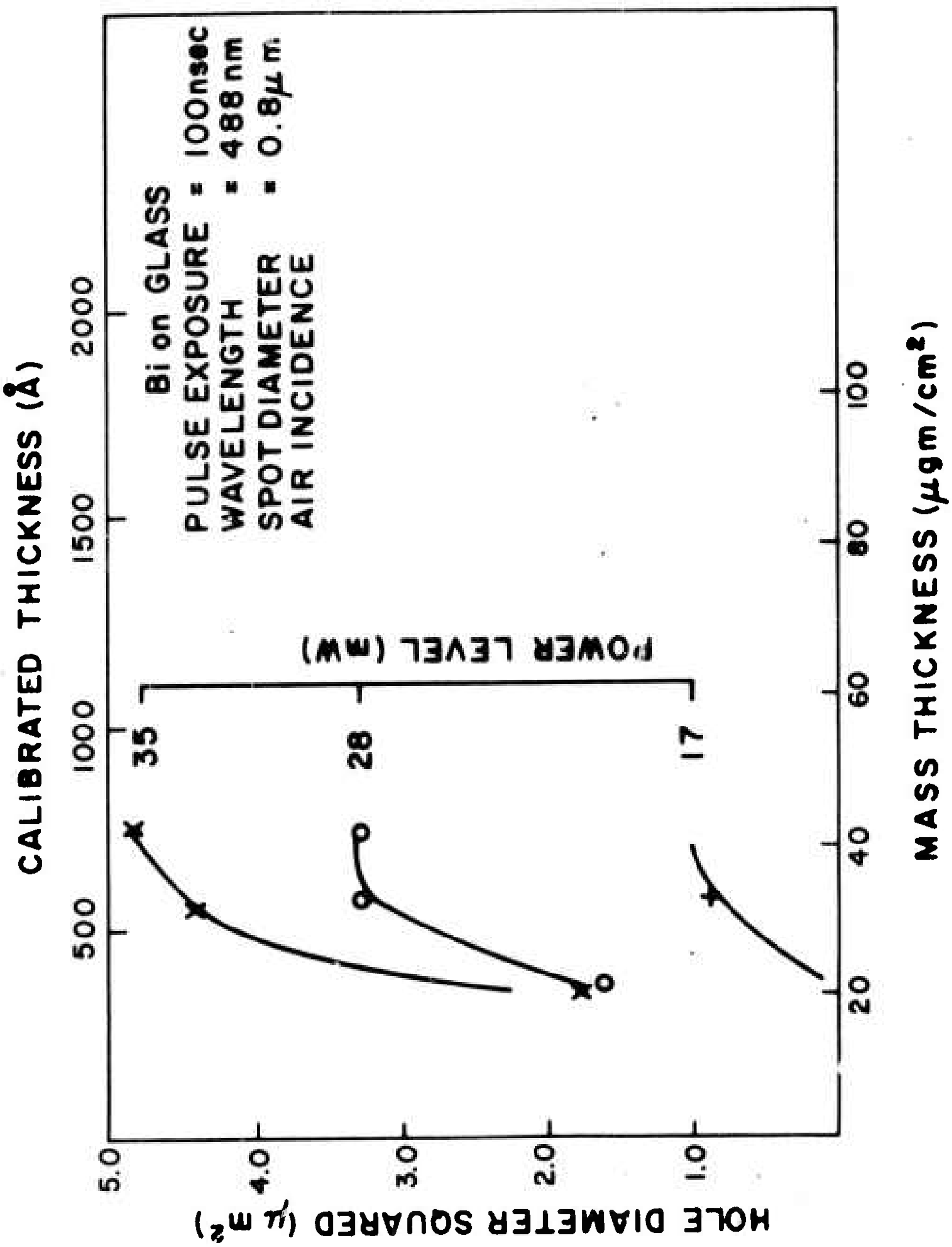


Figure 3d: Sensitivity for bismuth films to laser micromachining.

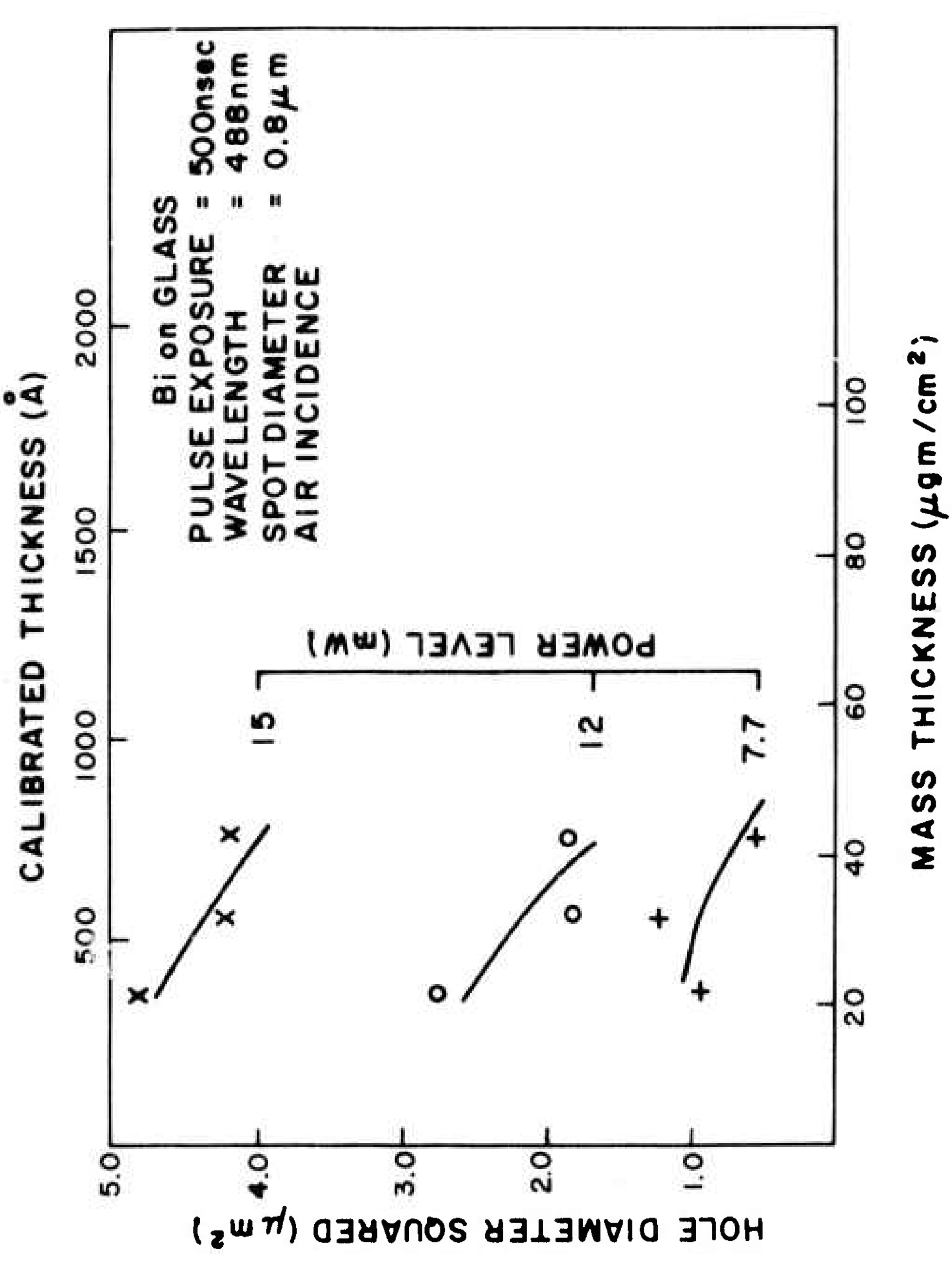


Figure 3e: Sensitivity for bismuth films to laser micromachining.

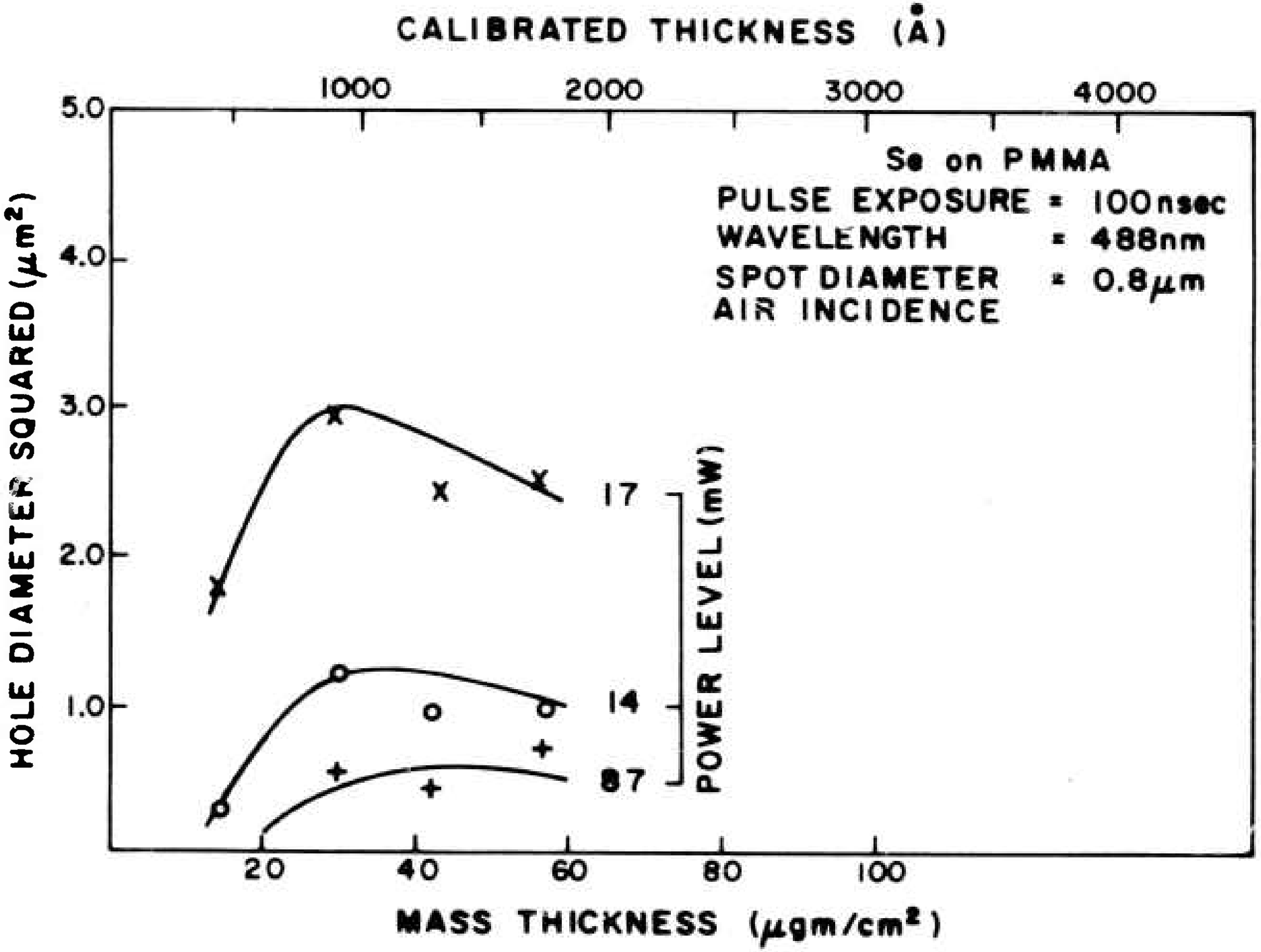


Figure 4a: Sensitivity of selesium films to laser micromachining.

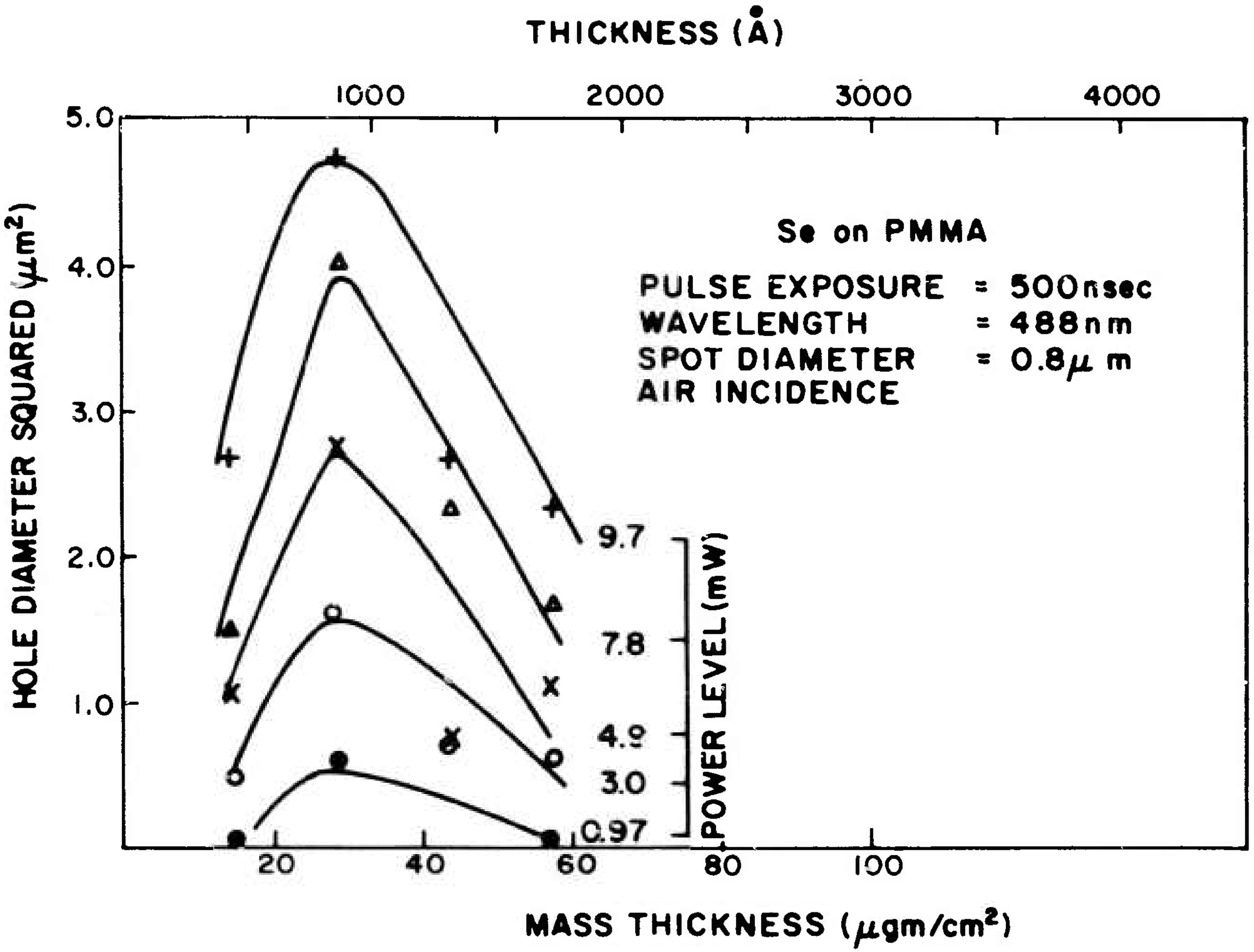


Figure 4b: Sensitivity of selesium films to laser micromachining.

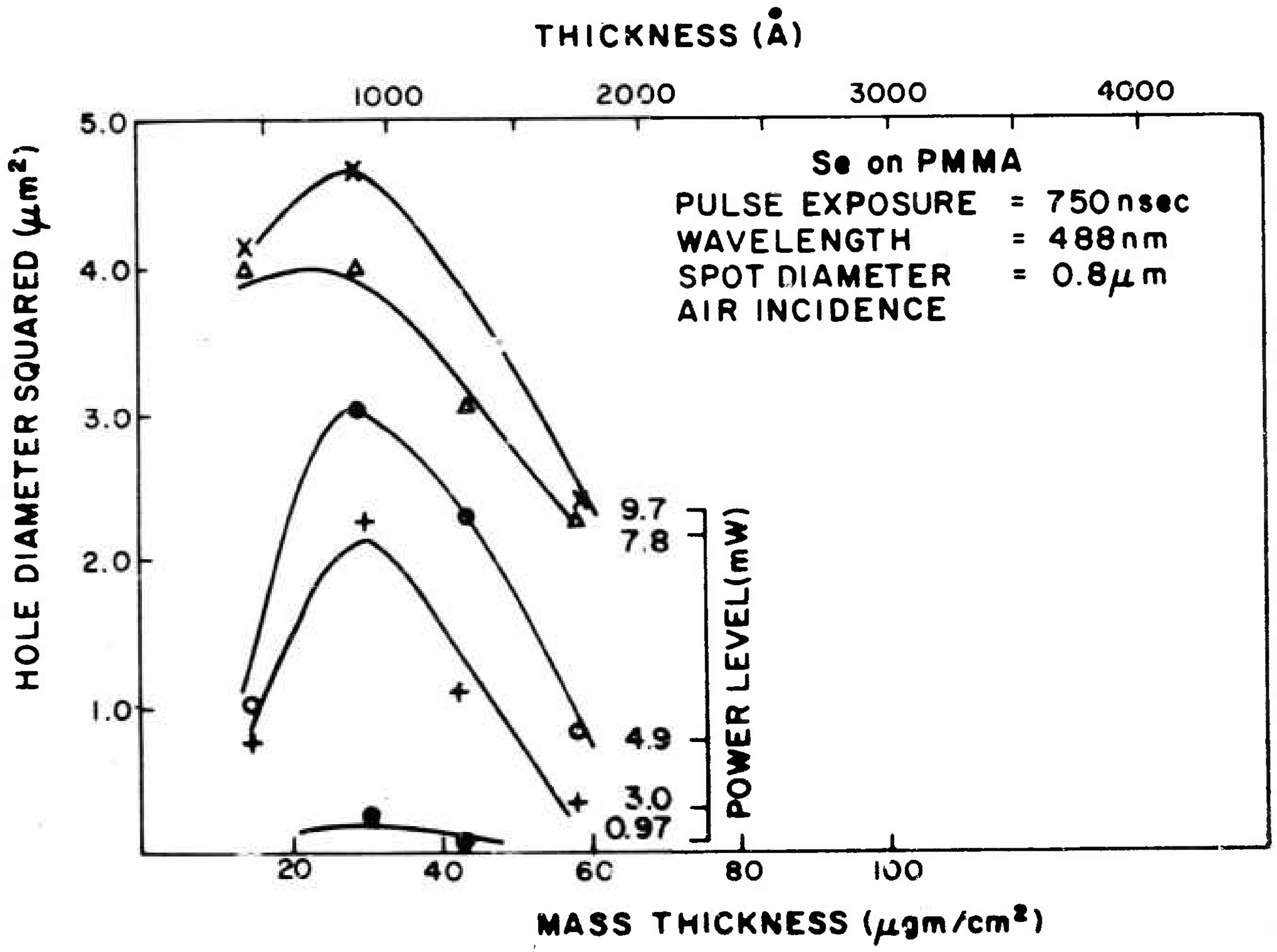


Figure 4c: Sensitivity of selesium films to laser micromachining.

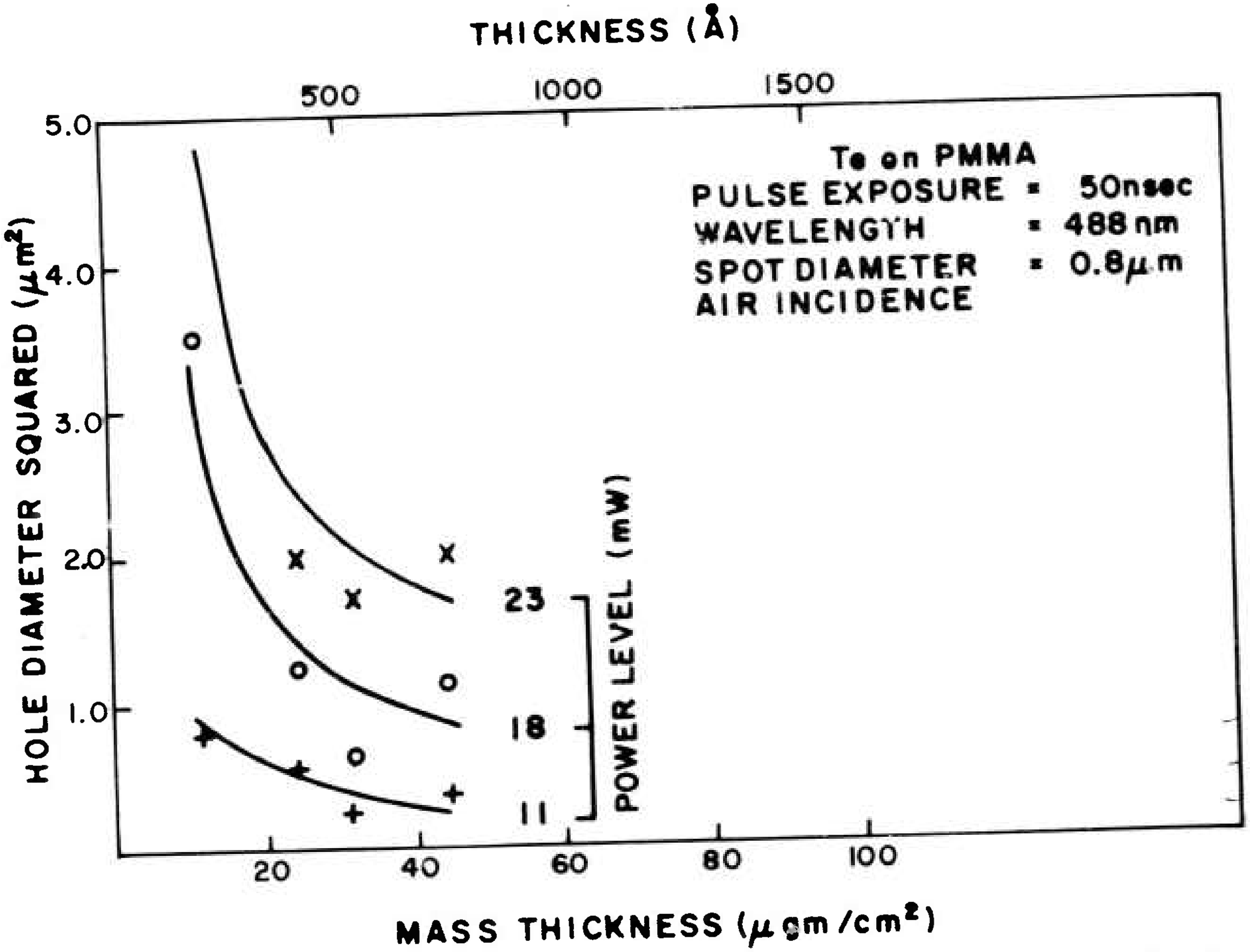


Figure 5a: Sensitivity of tellurium films to laser micromachining.

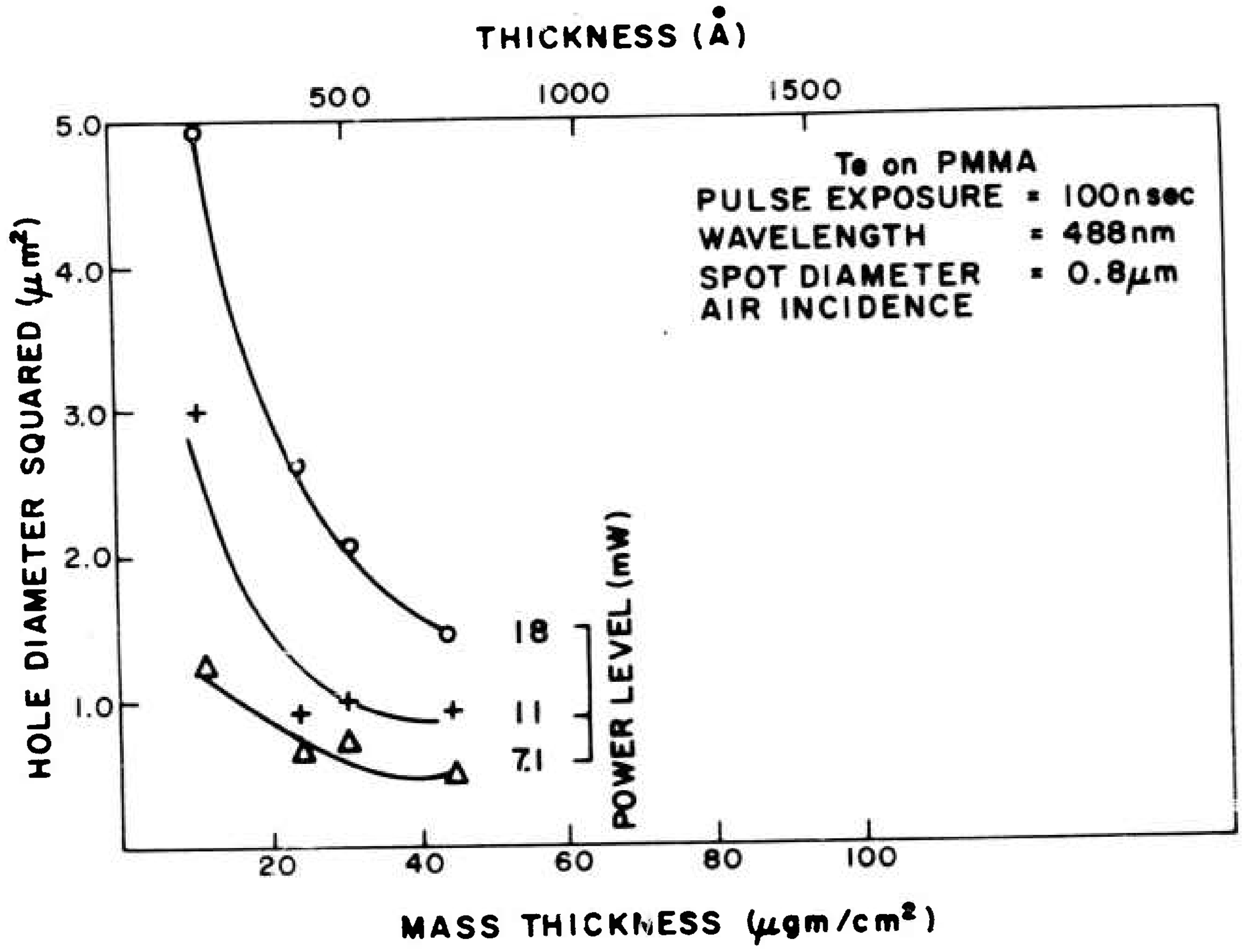


Figure 5b: Sensitivity of tellurium films to laser micromachining.

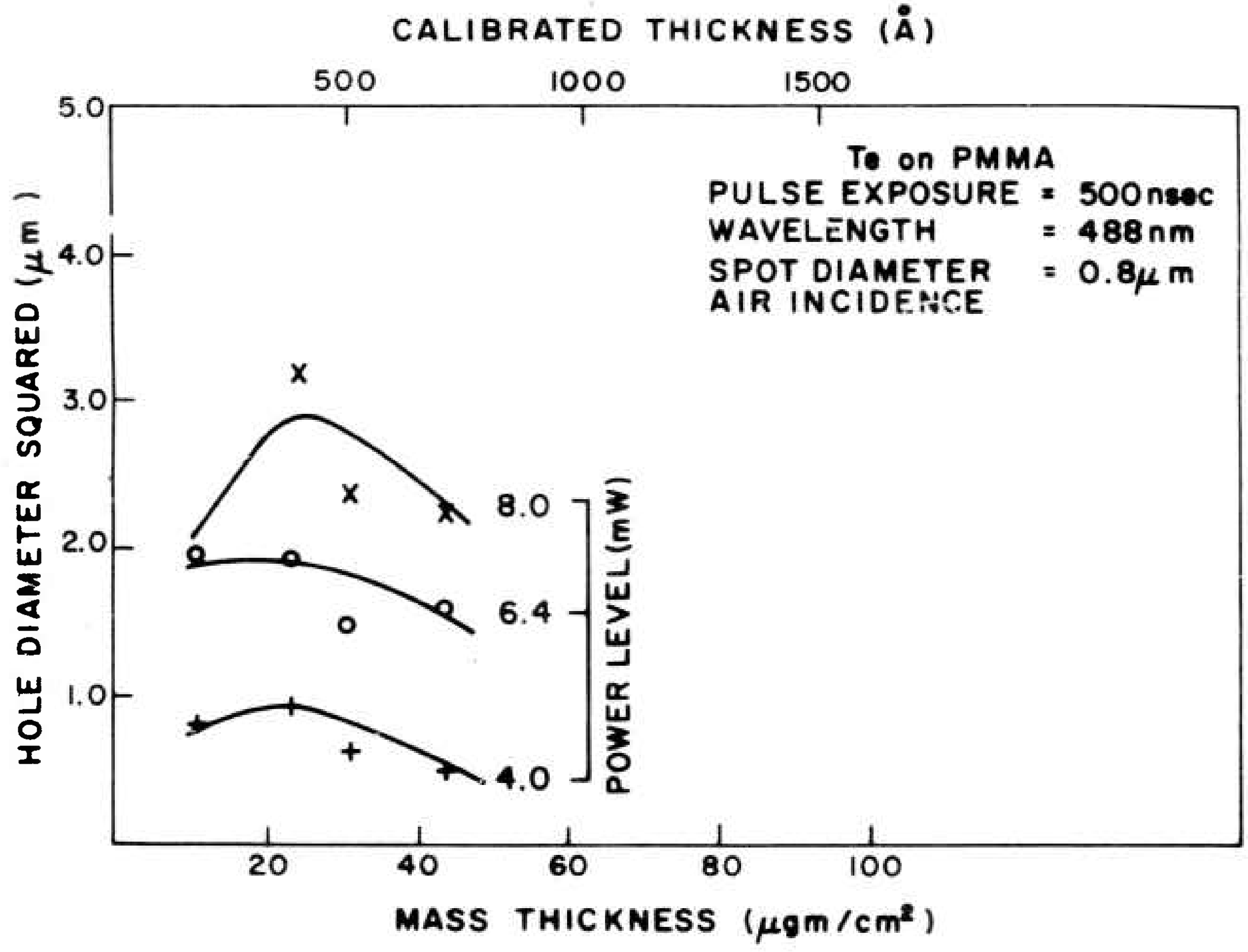


Figure 5c: Sensitivity of tellurium films to laser micromachining.

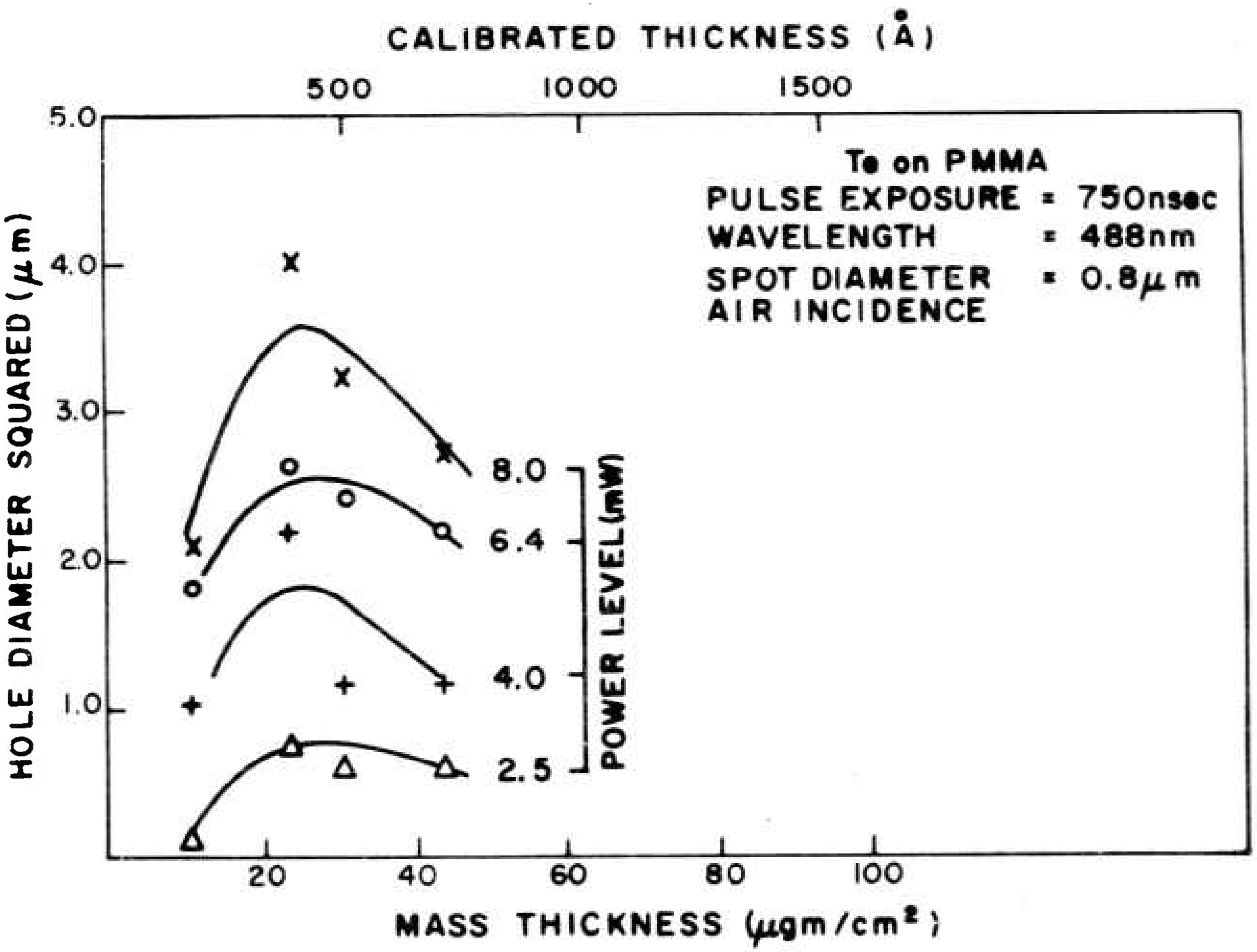


Figure 5d: Sensitivity of tellurium films to laser micromachining.

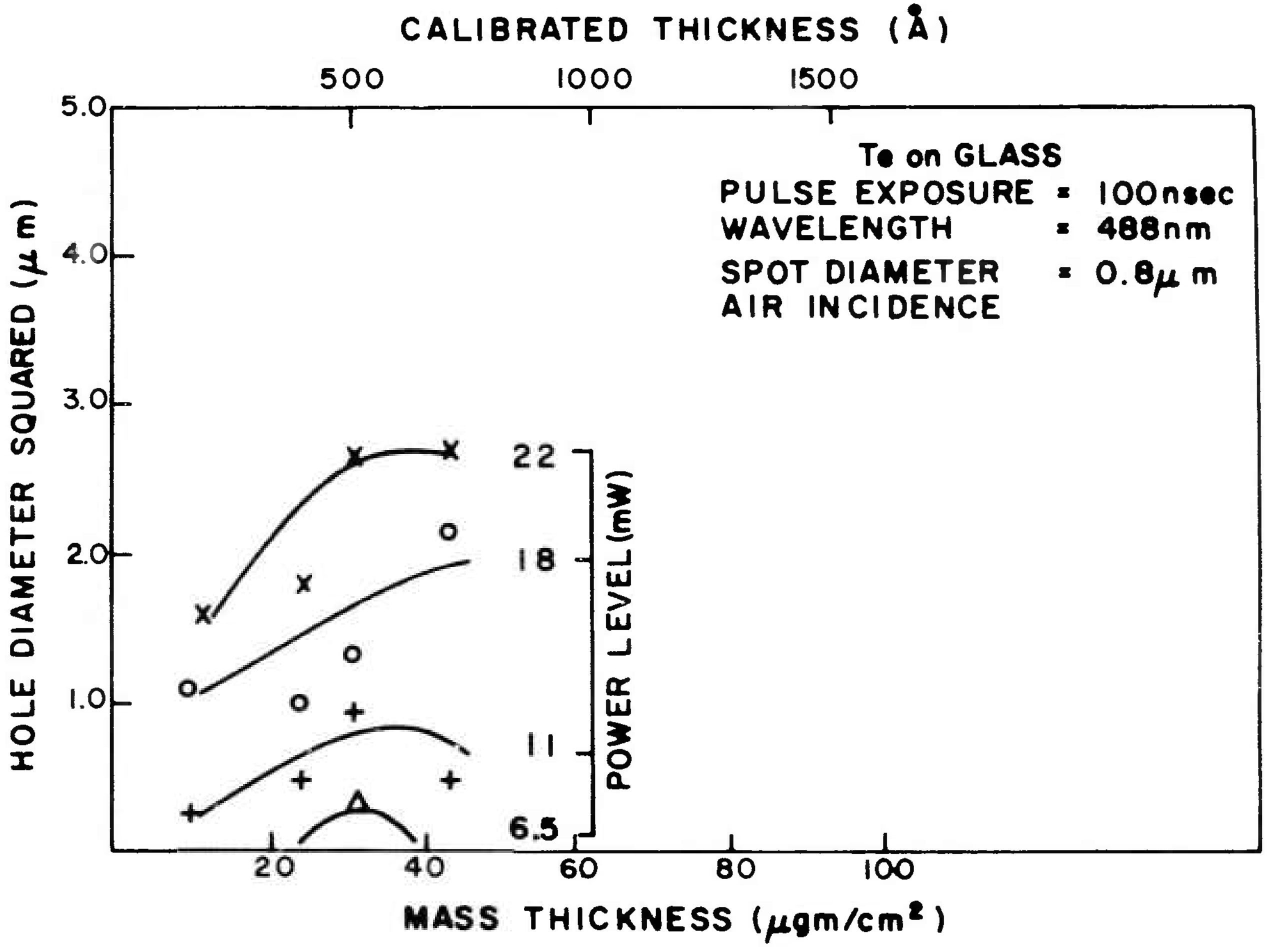


Figure 5e: Sensitivity of tellurium films to laser micromachining.

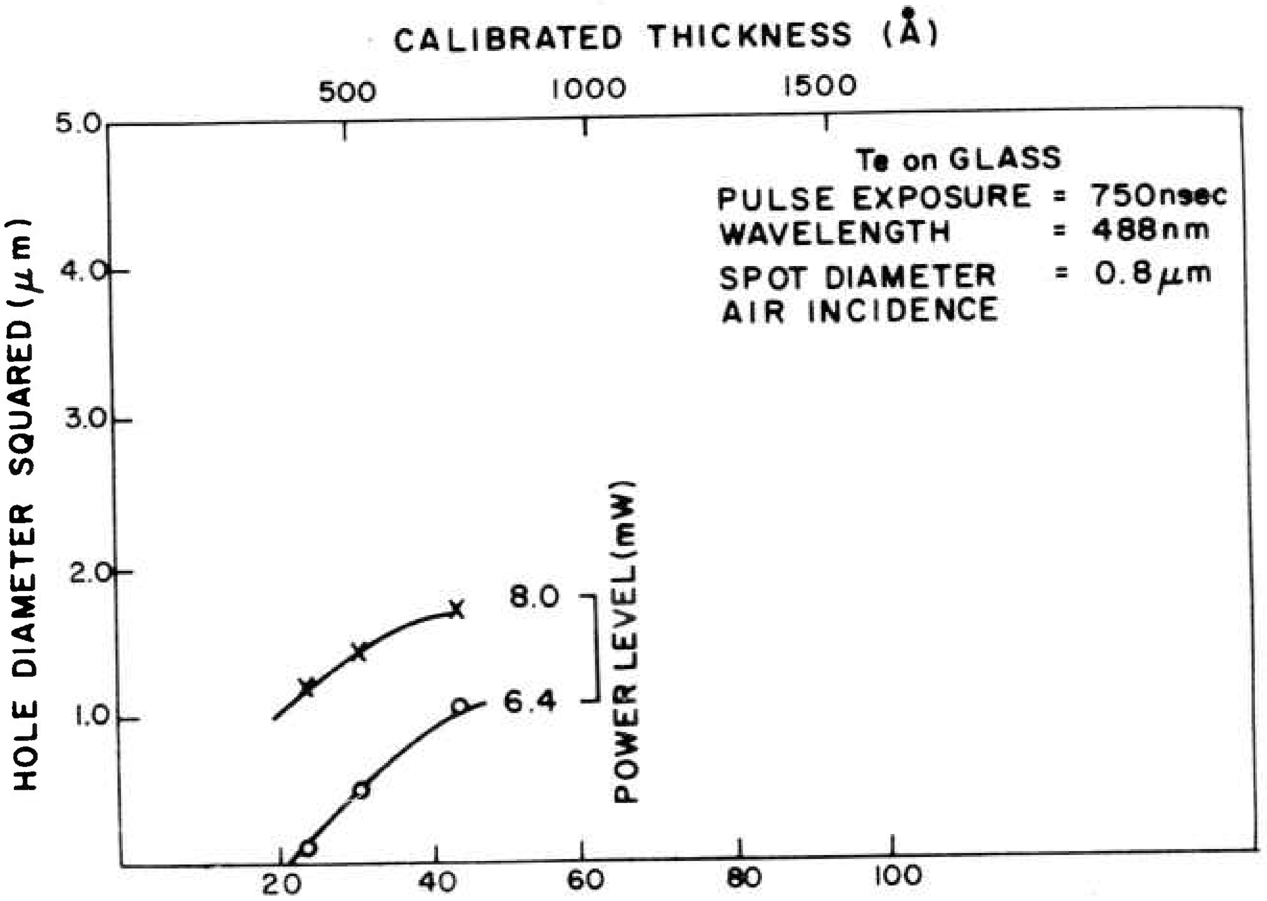


Figure 5f: Sensitivity of tellurium films to laser micromachining.

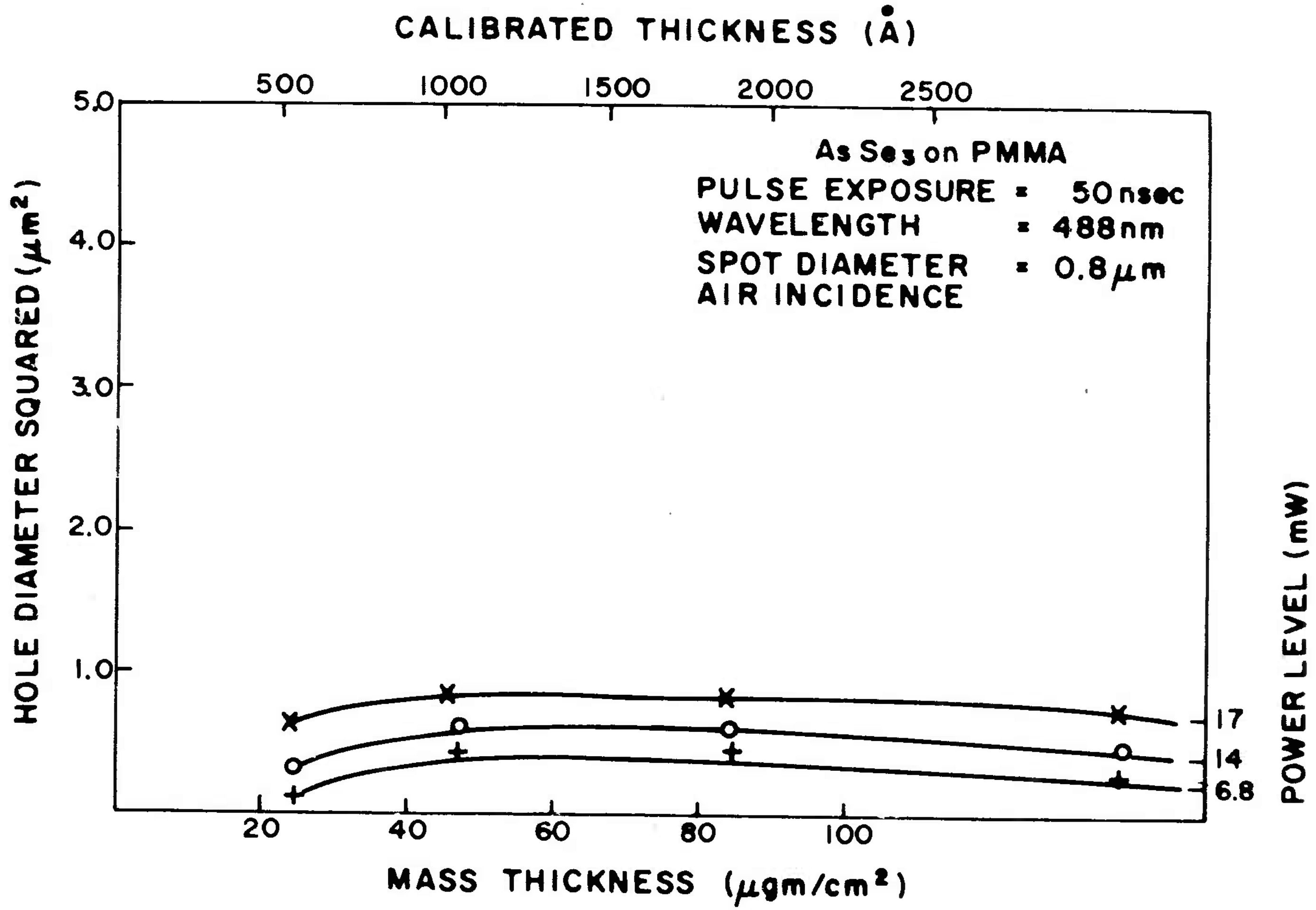


Figure 6a: Sensitivity of arsenic selenide films to laser micromachining.

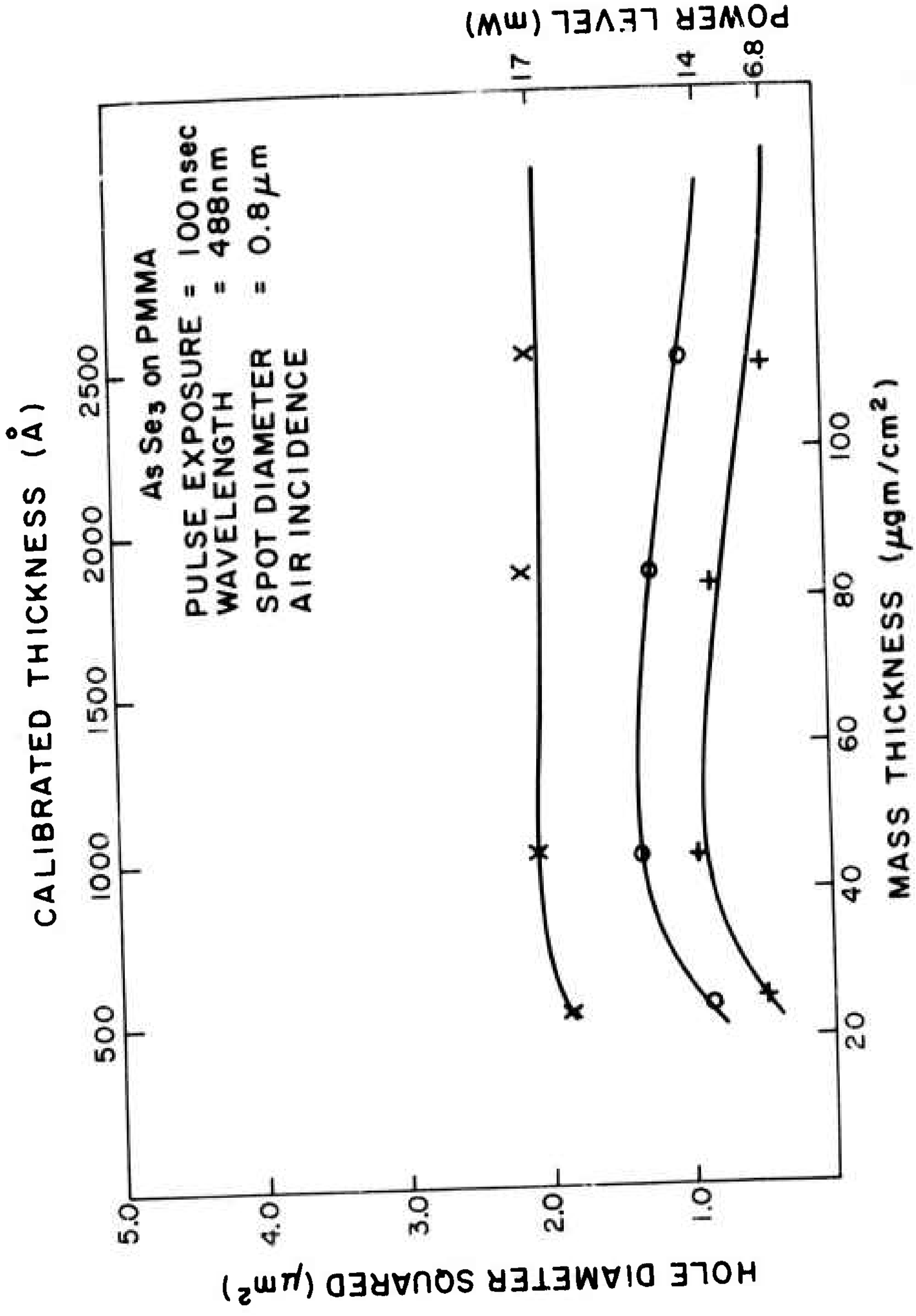


Figure 6b: Sensitivity of arsenic selenide films to laser micromachining.

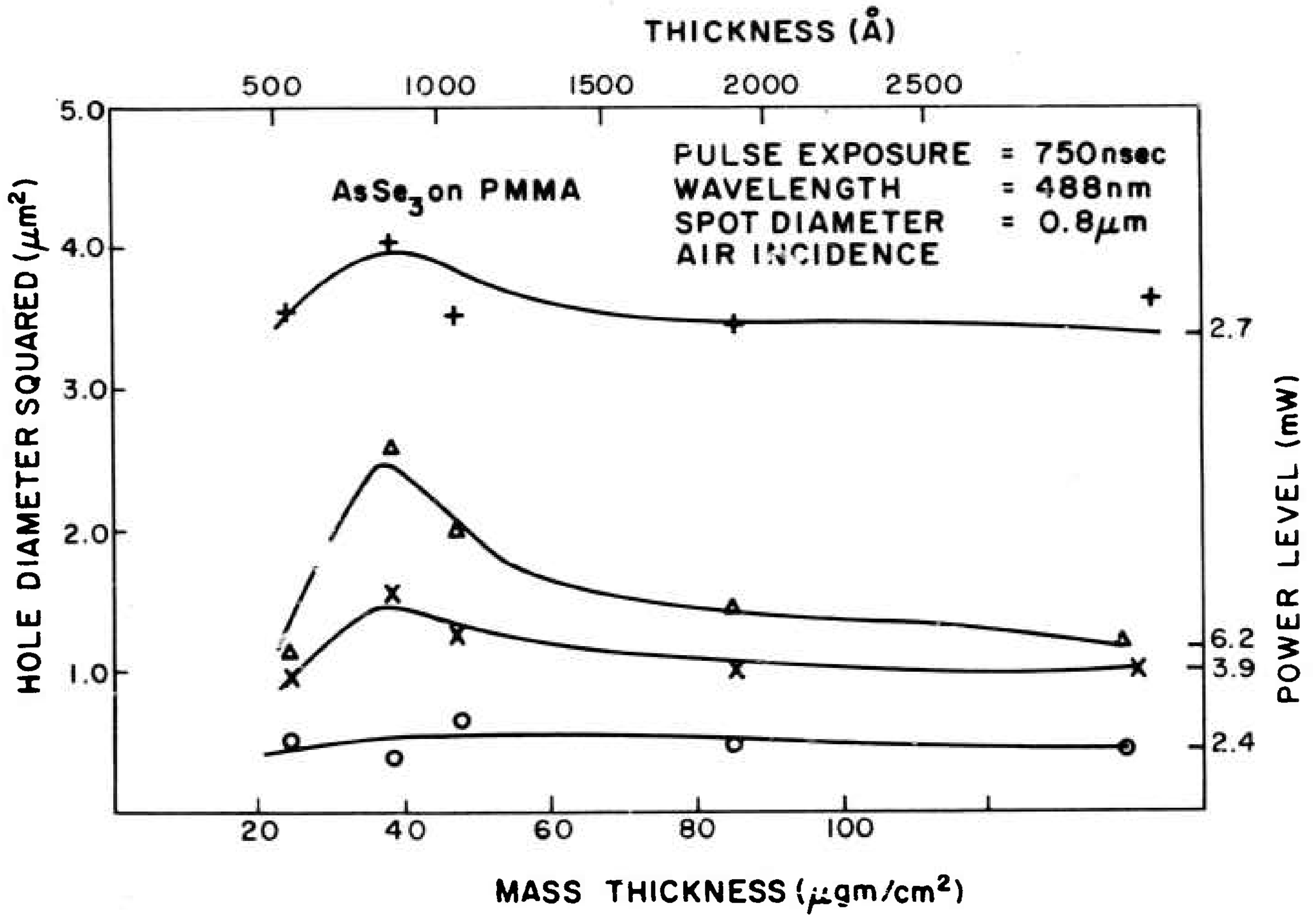


Figure 6c: Sensitivity of arsenic selenide films to laser micromachining.

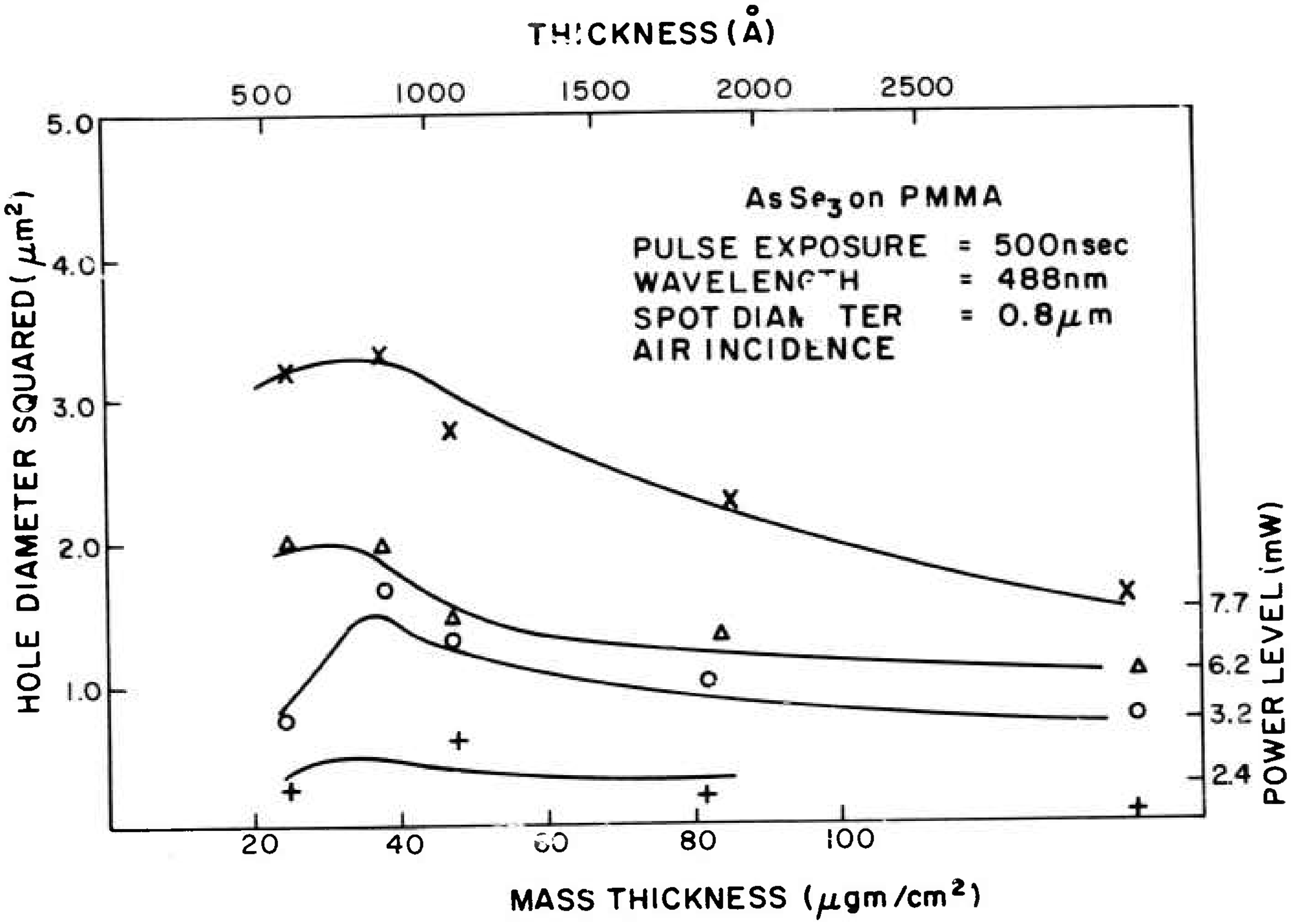


Figure 6d: Sensitivity of arsenic selenide films to laser micromachining.