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Characteristics of Current Filamentation in High Gain Photoconductive Semiconductor Switching*

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ABSTRACT

Characteristics of current filamentation are reported for high gain photoconductive semiconductor switches (PCSS). Infrared photoluminescence is used to monitor carrier recombination radiation during fast initiation of high gain switching in large (1.5 cm gap) lateral GaAs PCSS. Spatial modulation of the optical trigger, a 200-300 ps pulse width laser, is examined. Effects on the location and number of current filaments, rise time, and delay to high gain switching, minimum trigger energy, and degradation of switch contacts are presented. Implications of these measurements for the theoretical understanding and practical development of these switches are discussed. Efforts to increase current density and reduce switch size and optical trigger energy requirements are described. Results from contact development and device lifetime testing are presented and the impact of these results on practical device applications is discussed.

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INTRODUCTION

High gain photoconductive semiconductor switches (PCSS) are of technical interest because they are extremely fast, high power, solid state switches. As single components, they have withstood over 150 kV, conducted over 4 kA, and been activated with optical pulse energies less than 1 μJ. Table I lists parameters achieved with GaAs PCSS in the high gain switching mode. This optically efficient switching mode is often called lock-on or non-linear PCSS. It has been introduced and discussed in many other papers. The most recent work is found in the proceedings cited in references 1-4 and the papers cited therein.

This paper emphasizes experimental research on the initiation of this switching mode in Cr:GaAs. Previous experiments in collaboration with scientists at Boeing Aerospace and Electronics have shown that during high gain switching, the current is concentrated in filaments which extend across the normally insulating region (gap) of the switch[5,6]. Carrier recombination in Cr:GaAs is very rapid (1-2 ns) and normally results in the emission of a 1.4 eV (875 nm) photon. To monitor the location of high carrier or current densities, these first experiments recorded images of the infrared photoluminescence (PL) which was emitted from the PCSS during high gain switching. The use of this technique was continued in the experiments described in this paper where images of higher resolution and magnification are shown as laser intensity, position, spatial size, and location are varied. Results reported here show that the location of current filaments can be controlled and that significantly lower minimum optical trigger energies can be obtained by focusing the light to small regions near a switch contact. Controlling filament locations will probably allow the fabrication of more reliable switches with higher average current densities.

These experiments have three important implications for the theoretical explanations of this high gain switching mode. First, carrier gain in both polarities is seen across the entire gap of the PCSS, and it happens too fast for carriers to have been injected from the contacts and transported across the gap. Second, models which lead to S-shaped current-voltage characteristics should be pursued as it has been shown that these correspond to current filamentation[7]. Third, at least two-dimensional electrodynamic calculations are necessary to explain the inhomogeneous current densities which have been reported.

Current filamentation also has practical implications for device reliability and lifetimes. Contact development, device characterization, and lifetime testing are being pursued at our laboratories for the development of high gain GaAs PCSS. In collaboration with other laboratories[8,9,10], fabrication schemes using diffusion, ion implantation, and refractory metals are being tested. We are recording transient, light, I-V curves to characterize some devices and performing high repetition rate testing to provide device lifetime data. A description of this work and recent results are included in this paper.

CURRENT FILAMENTS

The goal for these experiments was to explore the current filamentation observed in the PL images as several parameters were varied. Higher magnification and better resolution pictures were obtained by using a different optics configuration which captured roughly sixteen times more light than the apparatus used previously. A black and white CCD video camera with a gated micro-channel plate intensifier was used to record the PL during high gain switching. This data was saved on video tape with some loss in quality.

All tests were performed with a 1.5 cm long by 2 cm wide lateral PCSS, which was fabricated from a 1" diameter by 0.025" thick wafer of Cr:GaAs. The PCSS was mounted in the tri-plate transmission line shown in figure 1. The width of the center plate in the transmission line was approximately the same as the switch width, so very little stray inductance or capacitance was added to the system by the switch. The system was pulsed charged with the voltage waveform shown in figure 2. The peak switch voltage for all high gain switching tests was 45 kV. However, timing jitter in the laser produced variations of a few kilovolts in the voltage across the switch at the time of switching. High bandwidth diagnostics and transient digitizers with a system bandwidth of approximately 3 GHz were used to record simultaneous laser and current pulse shapes. Optical pulses (200-500 ps wide) from a mode-locked, frequency doubled

(532 nm) Nd:YAG laser were used to activate the PCSS. Typical current waveforms for linear and non-linear switching are shown later in figure 9.

Until current filaments were observed, relatively uniform illumination was used to activate our switches. It was assumed that uniform illumination would lead to uniform current density. As this apparently was not the case, the effects of concentrating the optical trigger were explored. Figure 3 summarizes observations made with an infrared viewer after focusing the optical trigger to a narrow stripe. Significantly less light was required to trigger this size switch (1.5 X 2 cm^2). At the same voltages, several hundred microjoules had been required to activate the switch with uniform illumination at 532 nm. With a narrow stripe, as little as 1.5 μJ activated the high gain mode. The filament followed the light source even when it was more than 45 degrees off the axis of the average electric field. When focused near the negative contact, multiple filaments were observed with only 20 μJ of optical trigger energy.

Figure 4 shows similar results when the light is focused to a small point ($\sim$1 mm diam.). At low optical intensities ($<$ 10 μJ), the filament always intersected the point and even less light, as low as 0.5 μJ near the cathode, was required to activate the high gain mode. Triggering was easiest at the cathode, although triggering at the anode was achieved with 2-3 μJ. Since triggering at these fields with uniform illumination required several hundred microjoules, this represents a reduction in the laser triggering energy by another two orders of magnitude. Previously reported triggering gains of 1,000 may eventually be extended to 100,000. Further testing at high fields with low impedance circuits is necessary to verify this prediction. At high optical energies, the filaments did not intersect the point of optical illumination. Too much light may increase the local conductivity beyond optimum for high gain initiation. Triggering at the center of the gap required as much total light energy as uniform illumination over the whole switch. This implies much higher ($\sim$300 times) power densities were required when focused near the center of the gap than when uniform.

Since focusing to a point worked so well, the strategy of using fiber optics to produce multiple filaments is being explored. Fibers can theoretically couple individual laser diodes from large arrays to large PCSS with only minimal loss in brightness. We have started by testing relatively large, 1 mm fibers, and will eventually explore smaller fibers. Figure 5 shows two views of the 1 inch diameter PCSS which is clamped between cylindrical electrodes at the top and bottom of the pictures. The two fibers are visible over the negative contact in the lower half of the left photograph. The horizontal lines at the boundaries between the wafer and the electrons are the edges of metallic contacts. The right photograph (5B) is enlarged to show the insulating region of the switch between these contacts.

Filaments triggered with a single fiber are shown in figure 6. These photographs show only the active region of the switch (1.5 X 2 cm^2) with the contact edges at the top and bottom of the pictures. In this sequence of photographs, the fiber was moved from near the negative contact to about one fourth of the way across the 1.5 cm long gap. To maintain high gain switching, the laser energy had to be increased from a few microjoules to over 100 μJ as the fiber was moved away from the negative contact. Even at very high energies (> 500 μJ), high gain switching could not be initiated through a 1 mm fiber optic in the center of the gap. In the lower photographs (6C and 6D), the activating laser pulses are so intense that they produce a 1 mm diameter spot. This is caused by recombination of the carriers generated directly by the optical trigger pulse and is visible whether or not an external electric field is applied to the switch. As mentioned previously, the filaments tend to avoid these high intensity spots.

The upper right photograph (6B) shows a filament which abruptly loses intensity in the middle of the switch. This is probably a point at which the filament branched more deeply into the GaAs. Recombination radiation is strongly self-absorbed in the GaAs wafer, so only filaments within a few microns of the surface are visible. Both depth and current density affect the brightness of the emitted image. Some tests showed images with only one strong filament, while others showed a variety of branches ranging in size and brightness. Forking in both directions implies that growth occurs in both directions, but time resolved snap-shots are needed study this growth more carefully.

Filaments triggered with two fibers near the negative contact (bottom) are shown in figure 7 for different separations between the fibers. In the first photograph (7A), the separation was 1.7 cm. In the last (7D), the 1 mm fibers were against each other. Initiation of two simultaneous filaments at low optical energies (1 μJ) was very sensitive to the fraction of light in each fiber. Above 5 μJ, filaments were always initiated from each fiber. Sometimes, filaments from one fiber intersected those from the other fiber. Figure 8 shows photographs of filaments triggered with the laser focused to a 200 μm point which is visible near the bottom of the photographs. In some cases, many fine branches (not adequately reproduced in the figures) were initiated. The sizes of the filaments appeared to range from 50-300 μm.

The most remarkable aspect of these measurements was that triggering near a contact did not change the delay and rise time to high gain switching. Figure 9 shows the switch current waveforms for fifteen consecutive high gain tests and for three random linear tests. High gain switching was initiated through a 1 mm diameter fiber optic near a negative contact with 5-10 μJ of 532 nm radiation. Linear switching was produced with nearly uniform illumination of 50-100 J over the entire switch and six times the diagnostic sensitivity was used to record the current. In all cases, the digitizers were triggered with the laser pulse which activated the switch. Since light absorption is essentially instantaneous (< 1 fs), the linear current marks the time at which the light arrived at the switch for all tests. Multiple linear pulses show ~200 ps of jitter in the trigger and diagnostic system which is presumably due to the changing shape of the laser pulse. The delay between trigger illumination and high gain switching is about 4 ns and the rise time is approximately 2 ns. This is consistent with data reported previously for uniformly illuminated switches operating at this field (30 kV/cm)[11,12]. These papers reported a strong dependence of the delay and rise time on the electric field. At the lower end, 13 kV/cm, delays as long as 700 ns have been observed. At high fields, 100 kV/cm, delays were not recorded and rise times as fast as 300 ps were observed. However, at the fields being used for these tests, delays and rise times of a few nanoseconds are typically observed with uniform illumination. The jitter observed in the high current waveforms is larger than the linear jitter and is probably related to variations in the switch voltage and laser intensity at the time of switching. Note that the highest current pulses, which correspond to the highest initial switch voltages, have the shortest delays. It should also be mentioned that while switch behavior near the electrical and optical thresholds to high gain switching may help reveal the underlying principles of operation, the authors do not recommend these conditions for practical applications. Since switch rise time, delay, and jitter are all reduced at higher fields, we believe that practical devices should be operated at 50-100 kV/cm.

IMPLICATION FOR MODELS

Any model for the initiation of the high gain switching mode in GaAs must explain the magnitude and location of carrier generation. Uniformly illuminated non-linear switches have produced three orders of magnitude more carriers than photons absorbed. Focusing the optical trigger near a contact has produced two more orders of magnitude. So a model must account for the generation of 10^3-10^5 additional carriers in the switch. Furthermore, the images of carrier recombination radiation, i. e. pictures of current filaments, clearly show that both polarities of carriers extend across the entire gap of the switch. Since a photodiode has been used to show that this recombination radiation is simultaneous with the high gain switch current[5], the waveforms shown in the previous section imply that the carriers are created within 4-16 ns after the switch is illuminated within 1 mm of a contact (the current pulse is approximately 10 ns long). If all the carriers were generated instantaneously near a contact, they would have to move at 1-4 x 10^8 cm/s or roughly ten times the carrier saturation velocity in GaAs to cross the 1.5 cm long switch. Thus, any model which depends on carrier generation near the contacts will not explain this situation. A mechanism is needed to explain how a switch which is illuminated at a contact can rapidly initiate carrier generation across the entire switch. (Note that this reasoning did not rely on the space charge limit which has also been used to argue that all of the carriers cannot be generated near the contacts.)

High gain switching may be initiated rapidly by high electric field pulses or the recombination radiation which can cross the switch much faster than the carriers. This mechanism would be analogous to breakdown in gas or liquid discharge systems where intense field enhancements originate near the electrodes and produce avalanche carrier generation in their path as they grow and cross the gap[13,14,15]. Computer modeling of these conditions should check this analogy and highlight the significant differences. Important questions are: (1) what controls the size, intensity, and branching of the filaments; (2) What limits the current density in the filaments; and (3) what determines the rise time of the current pulse? More accurate data on these parameters and information on the time evolution of the filaments are required to test the theoretical predictions.

HIGH CURRENT DENSITY CONTACT DEVELOPMENT

The high current density implied by these filaments, which is estimated to be greater than 10^6 A/cm^2, is probably the predominant factor contributing to device lifetime. Most of the degradation which is visible on high gain PCSS is near the contacts. Table I lists the lifetime (10^5 shots) obtained with small 2.5 X 2.5 mm^2 GaAs PCSS switched at 1 MW. These switches were fabricated with a simple Au-Ge contact which is an industry standard. The failure mode of these devices is electrical breakdown across the surface of the insulating region. This surface flashover generally leaves a conducting path or fractures the switch. Initiation of the breakdown appears to come from regions near the contacts which have been significantly damaged during previous shots.

Contact damage may be caused by poor adherence of the metal to the semiconductor, large electric potential barriers at the metal-semiconductor interface, high current densities due to current pinching or filaments, and gradual degradation of the interface due to elevated instantaneous temperatures. Many suggestions have been offered to reduce these types of contact problems[1,2]. We are attempting to test as many of these ideas as possible at our laboratory with our switches and those fabricated by collaborating scientists at other laboratories[8,9,10]. We solicit suggestions and are willing to test any switches which offer some potential improvement.

In addition to Au-Ge, we are testing contacts with refractory metals: Ti-Pt, Pd-Ge-Ti-Pt. To reduce the current pinching problem near the contacts, we are trying diffused or ion implanted conductive layers below the metal layers. More sophisticated fabrications involving epitaxial growth, and/or etched trenches with back-filled metallizaton have been proposed and may also be tried.

The circuit used to perform device lifetime testing is described in a previous paper[16]. Switch voltage and current waveforms for linear and non-linear switching are shown in figure 10. To characterize these switches and their contacts, we use the peak currents and simultaneous on-state voltages from these waveforms to derive transient, light, current-voltage curves such as the one shown in figure 11. The switch is triggered with a 150 W (peak) laser diode array. Many waveforms are recorded over a range of charging pulse voltages. The peak current is linear in the switch voltage, until a threshold is surpassed. Above this point, the current increases by two orders of magnitude, and the voltage across the switch drops. The authors are pursuing transient I-V curves for illuminated switches because these characteristics are more representative of their standard operation conditions. The dark resistance of these switches is so high (10^7-10^8 Ω-cm) that even at these high voltages dark currents are small and dominated by capacitive effects in transient tests ($\rho\varepsilon \simeq 100\ \mu s$). Transient tests are performed so that thermal effects are minimal.

After characterizing a switch with transient, light, I-V curves, it is tested in the high gain switching mode to destruction, or until its switching properties change significantly. A 150 W, pulsed, semiconductor laser diode array (LDA) is used to activate the switch at repetition rates up to 1 kHz. The current is monitored and the number of high current pulses is recorded with a discriminating counter. Initial tests on switches with new contacts have always shown problems. New fabrication steps often lead to lower surface breakdown strengths. Switches with ion implanted, conductive layers below the contacts appear to require more light or electric field to activate. Conductive layers may help the current pinching problem, but they probably reduce the local field enhancements. If field enhancements near the contacts play a significant role in the initiation of non-linear switching, then higher average fields maybe required. Under these test conditions with the current and voltage waveforms described above, our standard GaAs PCSS with Au-Ge metallized contacts last several thousand pulses. Tests on the first runs of ion implanted and refractory metal switches have shown devices with lifetimes ranging from several hundred to 5,500 shots. In some of the new devices, there has been a noticeable buildup of what appears to be contact material migrating to the center of the switch. Chemical analysis is being pursued to determine the cause of this effect. The authors and their collaborators will continue to make iterative corrections to the fabrication processes which are being developed as lifetime tests reveal their weaknesses.

CONCLUSION

Experiments with focused laser beams and fiber optics have produced several important results. Focused optical pulses near the contacts have produced as much as two more orders of magnitude in trigger gain, bringing the estimated total trigger gain at high fields and low impedances to 10^4-10^5 e-h pairs per activating photon. Initiation of the high current switching mode produces both polarities of carriers across the 1.5 cm gap within 4-5 ns. This implies substantial carrier generation in the insulating region of the PCSS away from the contacts. The location of the filaments is controlled by the location of the optical trigger. Multiple filaments can be triggered simultaneously by two optical fibers. Higher resolution photographs set upper limits on the filament diameters ranging from 50-300 μm. These results indicate that smaller switches with higher average current densities may be possible. More optical fibers with smaller diameters will be tested in the future.

New types of high current density contacts for GaAs are being developed. Results from lifetime tests on the first generation of some of these devices have not yet shown significant improvement. Problems associated with the new procedures are being studied and eliminated to reveal the strengths of these contacts in successive fabrication runs.

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Figure 1. These drawings show the high bandwidth (4 Ghz), enclosed tri-plate transmission line and diagnostics used to test high gain switching with GaAs PCSS. Photographs of current filaments were obtained from their infrared photoluminescence with a shielded, black and white, image intensified CCD camera mounted directly above an opening over the switch.

Figure 2. These waveforms show the test voltage produced at the left side of the transmission line which is in the previous figure.

Figure 3. These diagrams summarize the filaments observed with an infrared viewer when the optical trigger was focused to a stripe. Triggering at this voltage with uniform illumination required 200-300 μJ.

Figure 4. These diagrams are similar to those in the previous figure, except the optical trigger is focused to a point in these. Even less light is required when the light is concentrated near a contact.

Figure 5. Enlarged views are shown of the switch being tested in the following figures. Two fiber optics are visible in the lower half of A. The image in both photographs is distorted where the fibers enter the surface of the oil in which the switch is immersed. The horizontal lines are reflections off cylindrical clamps and contacts to the PCSS. The insulating region in the center of the photographs is 1.5 cm high by 2 cm wide at the boundary of the contacts. B shows only the insulating gap of the PCSS and the edge of the contacts.

Figure 6. These current filaments were produced by activating the PCSS with a 532 nm optical pulse through a 1 mm diam. fiber near the lower contact. The end of the fiber was located against the switch various distances from the lower contact: approximately 0 mm for A, 1 mm for B, 2 mm for C, and 4 mm for D. Recombination of carriers generated directly by the laser is evident in the 1 mm diam. spots near the bottom of C and D.

Figure 7. Twin groups of filaments are shown in these photographs. They were produced with two 1 mm diam. fibers which were illuminated simultaneously and positioned with different separations along the bottom contact of the PCSS

Figure 8. In these tests, the laser was focused to a 200 μm point which can be seen at the bottom of the photographs. The filaments tend to avoid regions of high illumination.

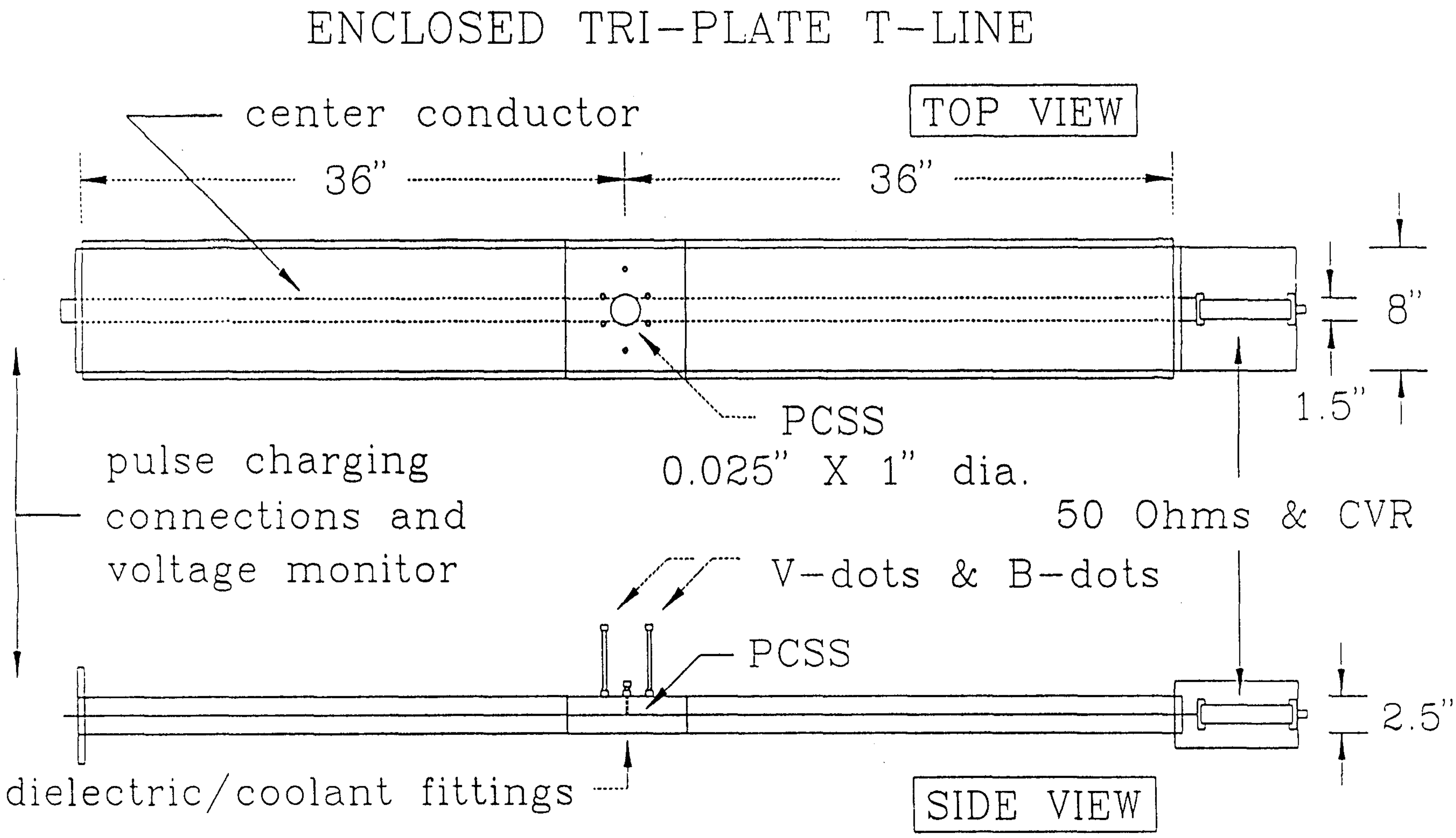
Figure 9. Current waveforms for linear and non-linear switching are shown on this graph. The linear waveforms mark the time at which the optical trigger reaches the PCSS. Since the linear current is much weaker than the non-linear current roughly ten times more optical energy was used and the corresponding waveforms were multiplied by 50 for visibility on this graph.

Figure 10. The voltage across and the current through a 2.5 mm long PCSS when being characterized and tested for reliability.

Figure 11. A light, transient, current-voltage characteristic which was derived by plotting the peak currents vs. simultaneous on-state switch voltages from a family of waveforms

similar to those shown in the previous two figures. Each point represents a test at roughly constant optical illumination as the system charging voltage was varied.

Table I. Characteristics of high speed, non-linear switching in large (1-30 mm long) GaAs PCSS[16].



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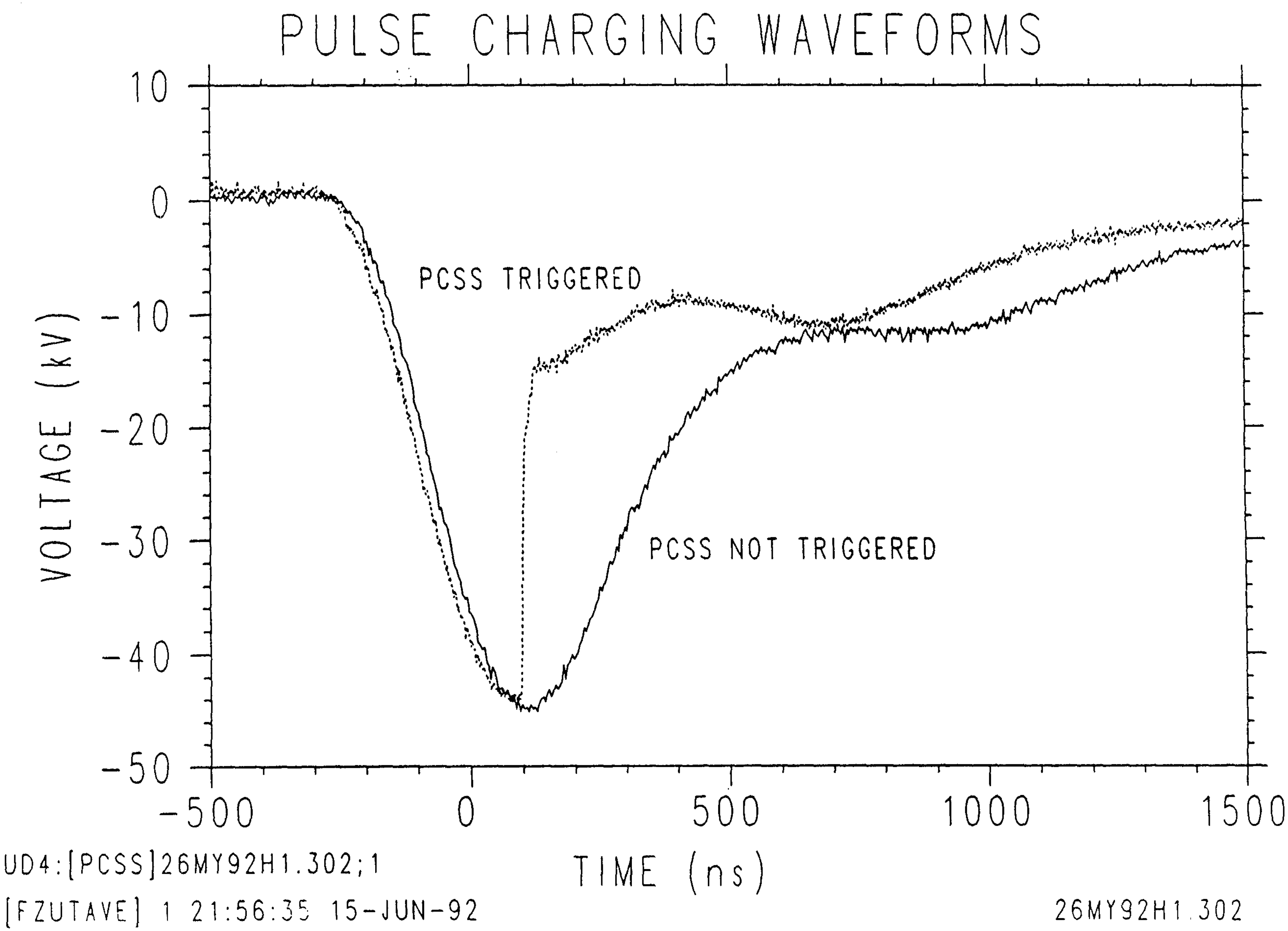

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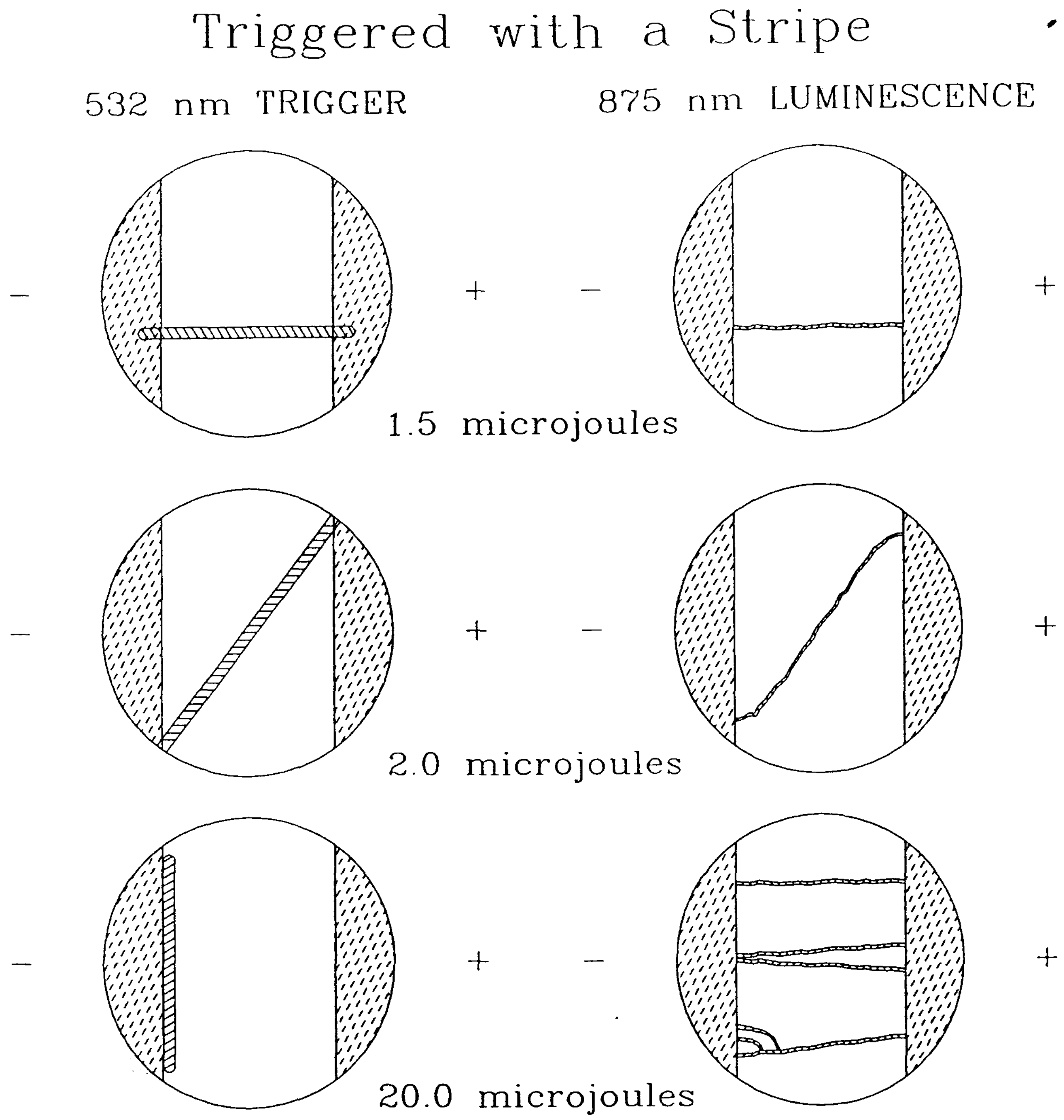

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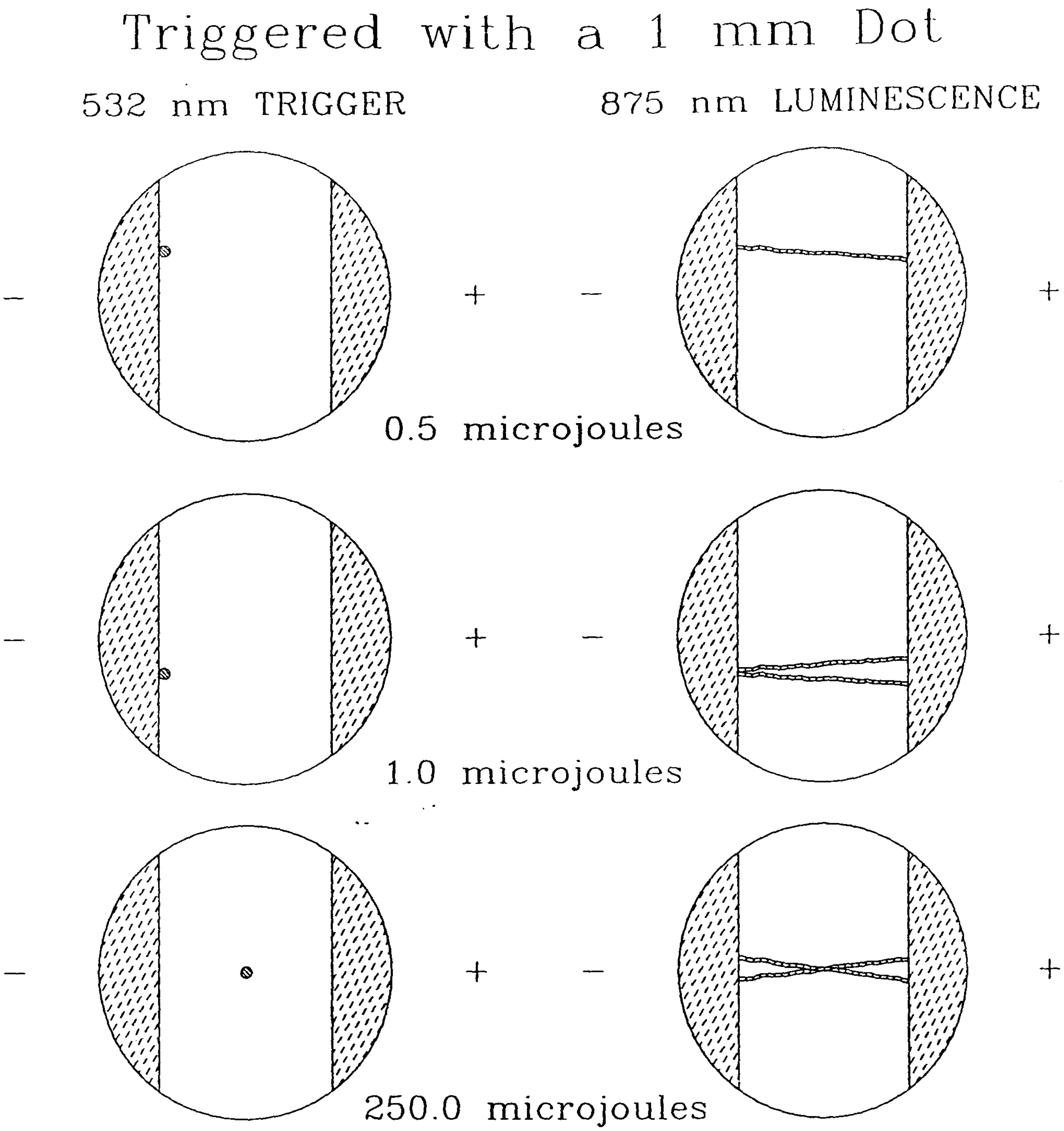

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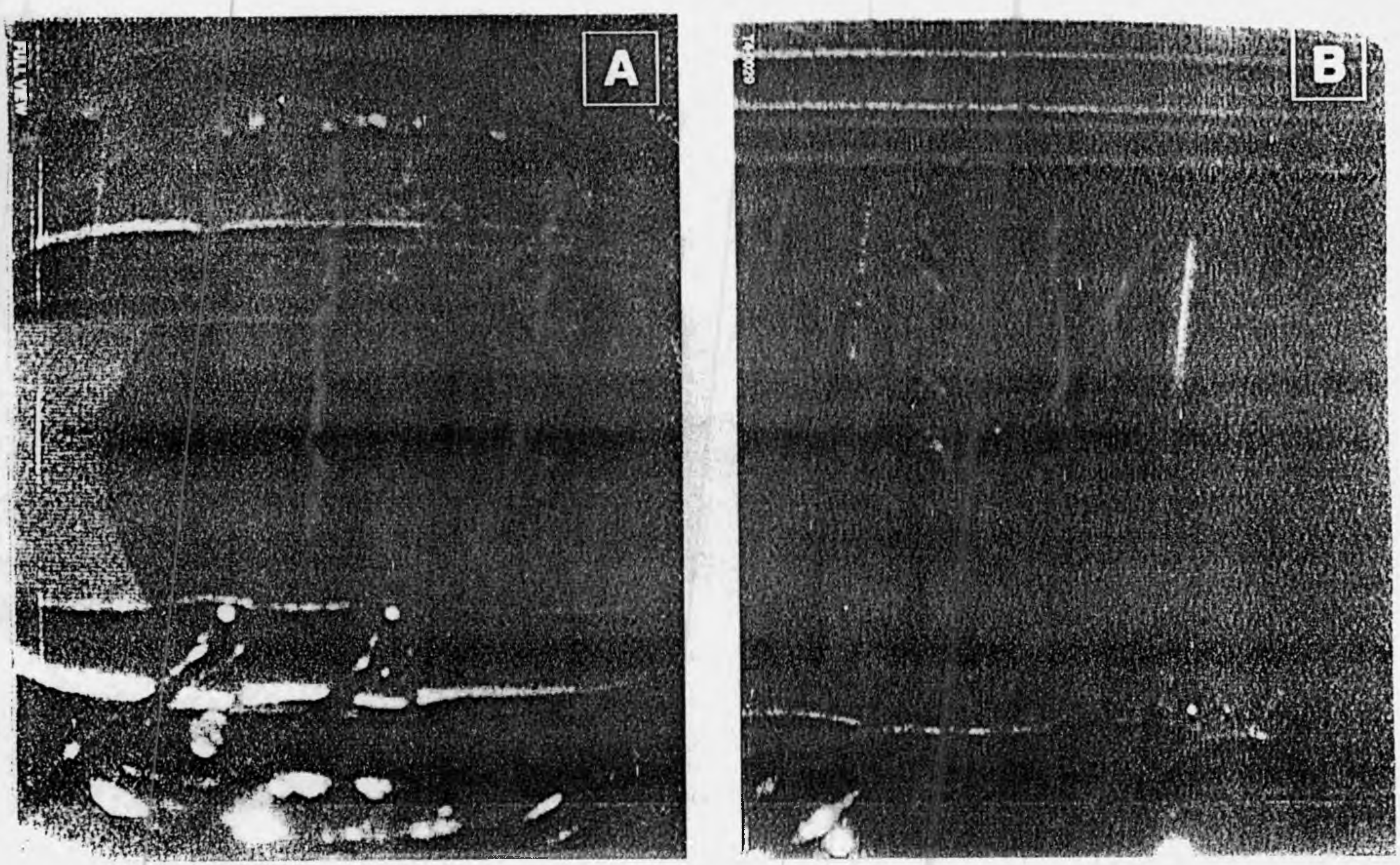

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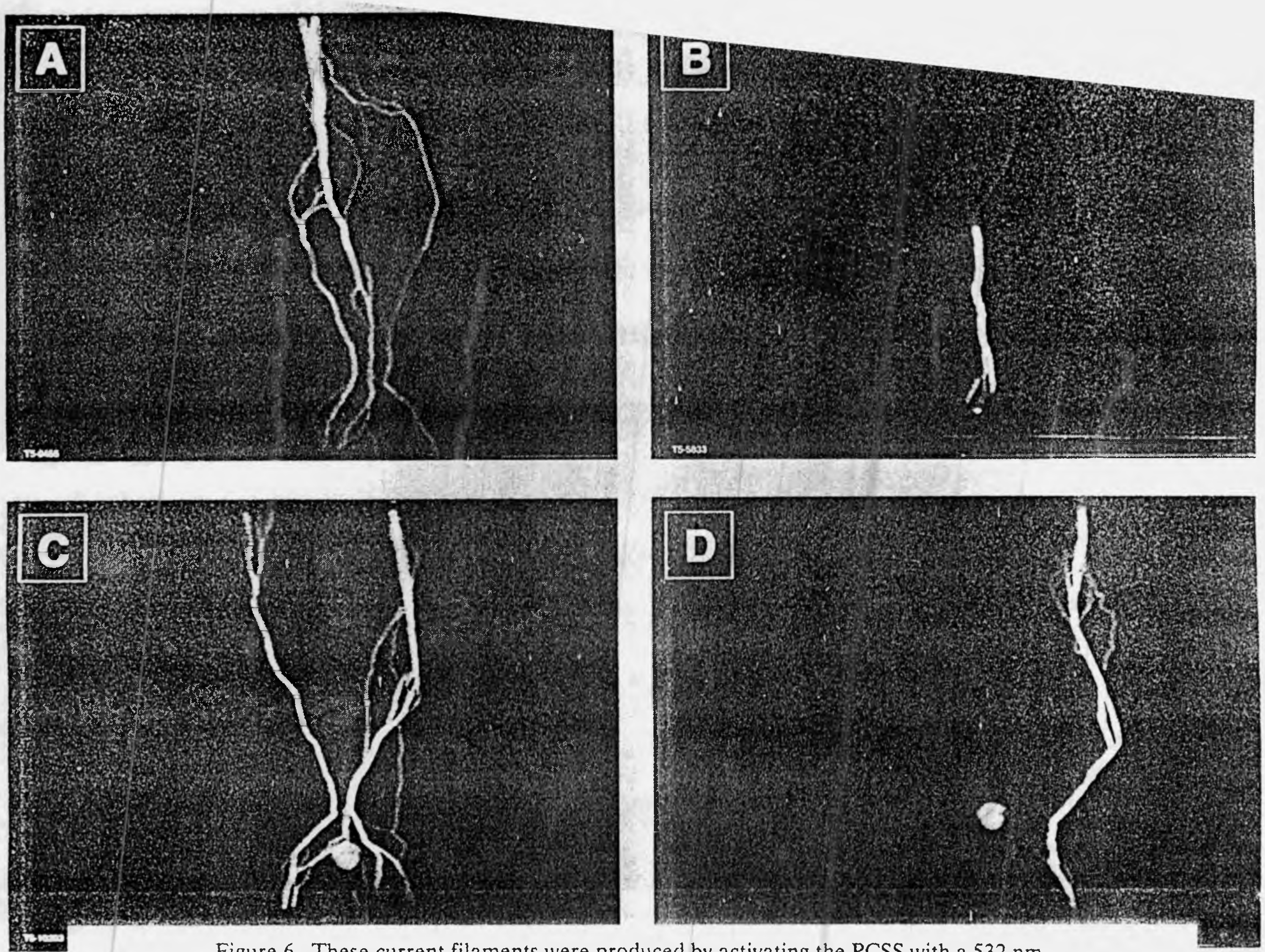

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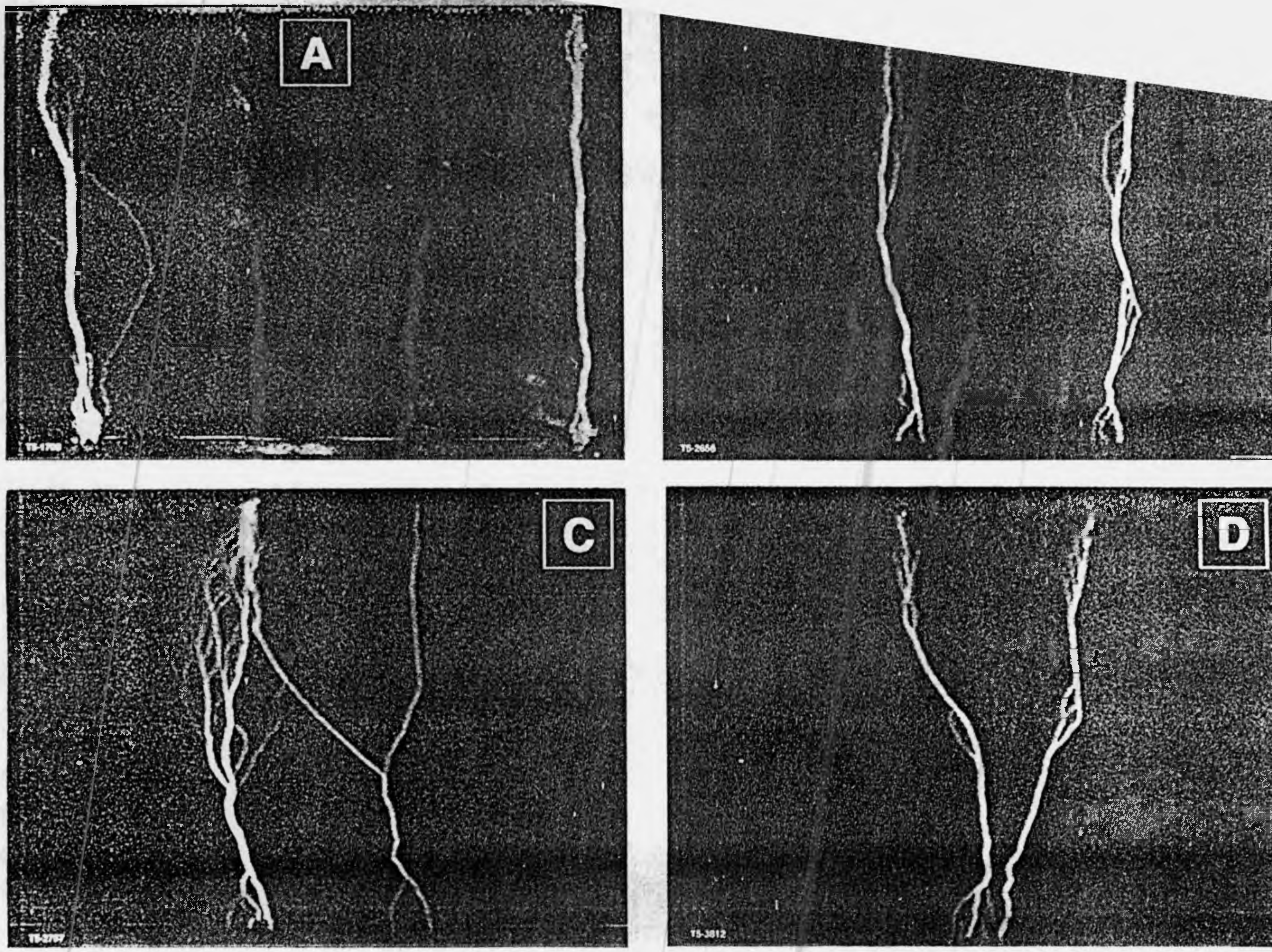

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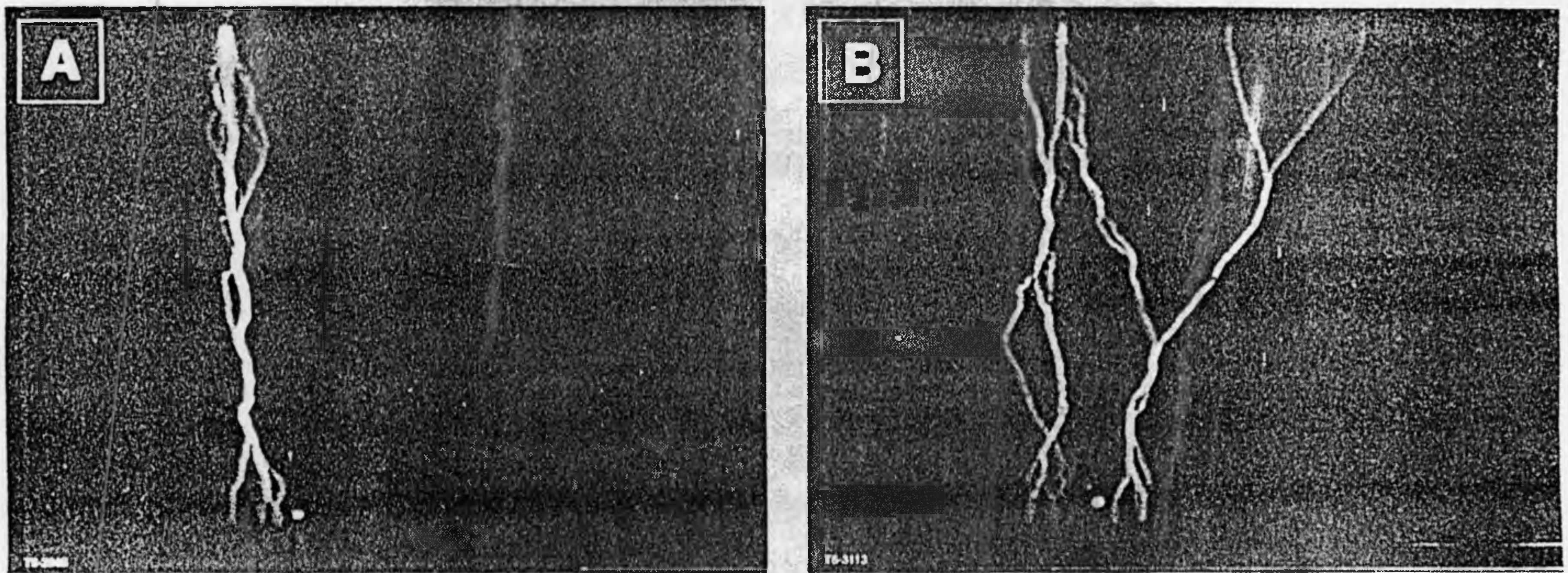

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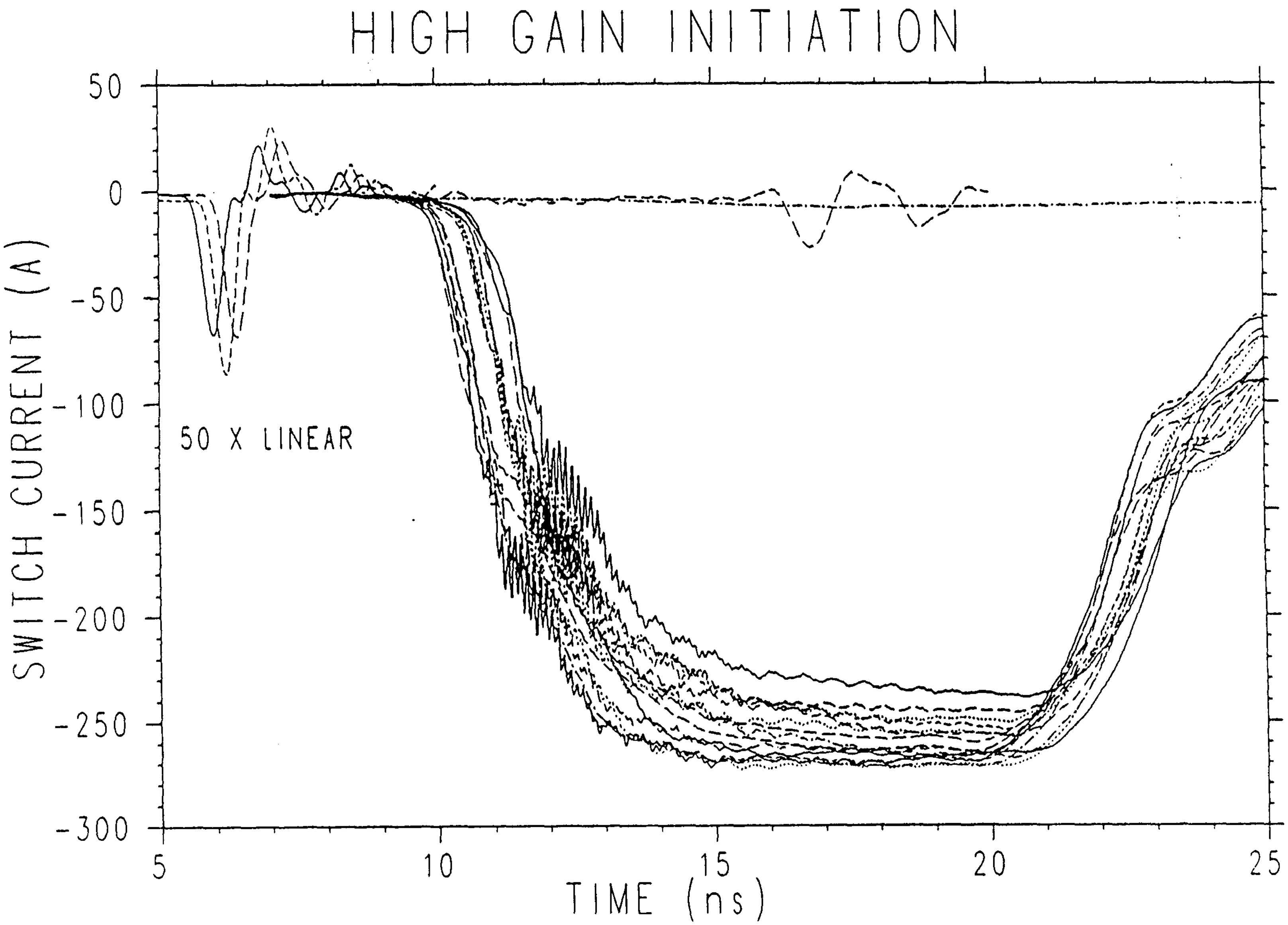

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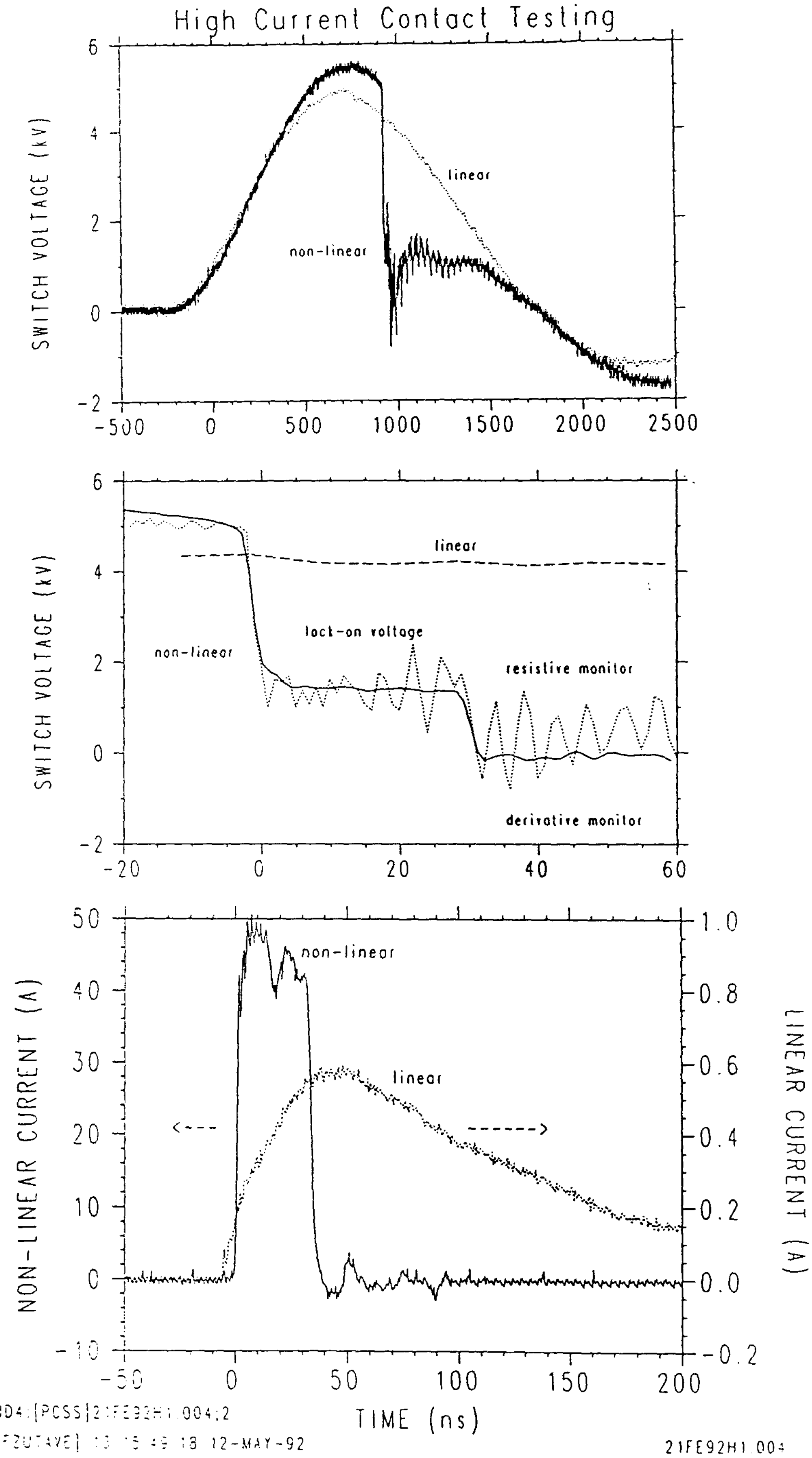

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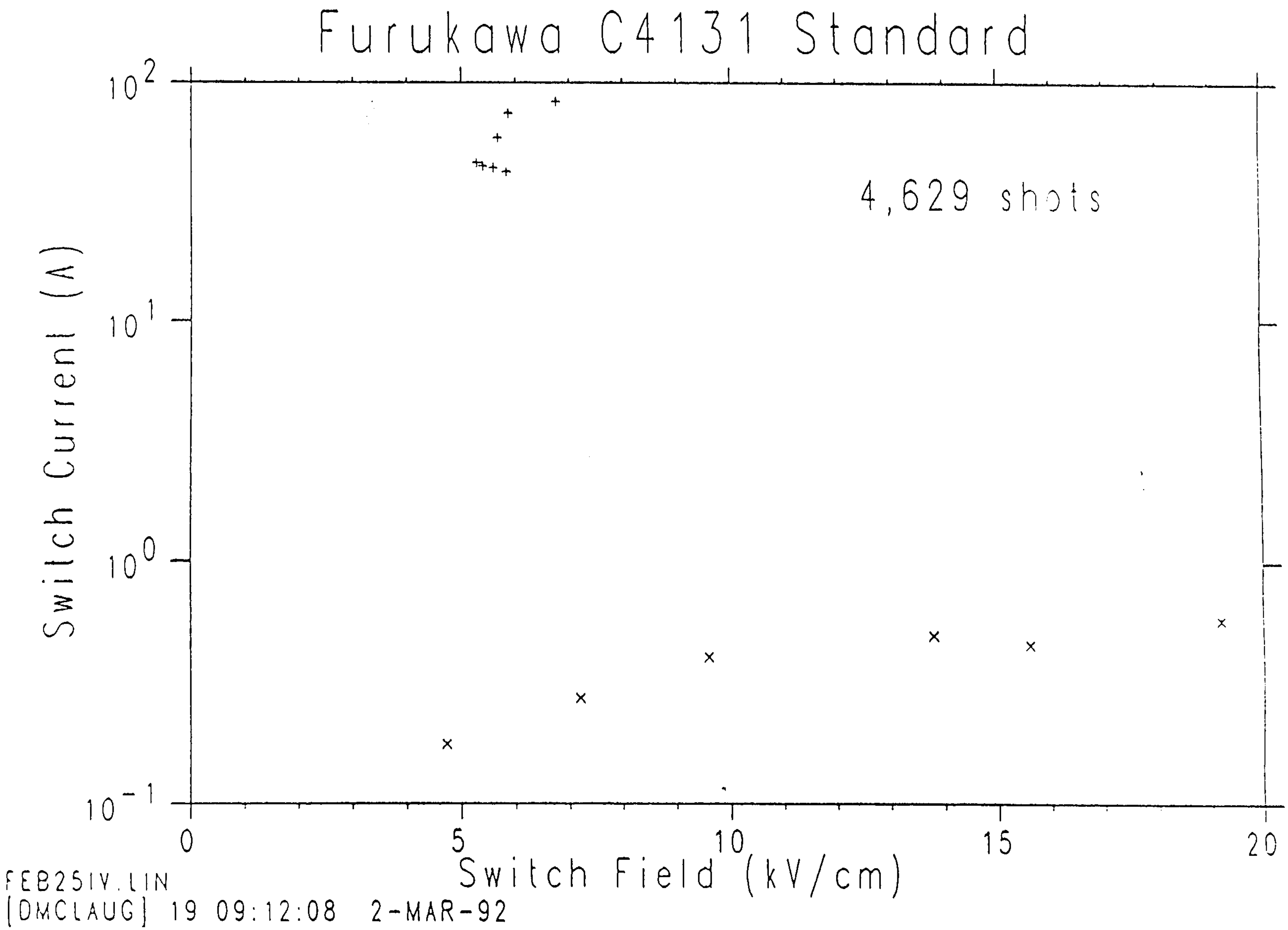

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High Gain GaAs

Summary of Results[1]

Parameter	with flashlamp pumped laser[1]	with laser diode array[1]
ELECT. FIELD (kV/cm)	57-100	37-100
VOLTAGE (kV)	155	70
CURRENT (kA)	4.0	4.2
POWER (MW)	120	40
RISETIME (ps)	300	600
DEVICE LIFETIME	not tested[2]	100,000
REP. RATE (Hz)	not tested[2]	1,000

[1] Results are not simultaneous.

[2] Limited by the laser.