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December 1, 1970

Research on

# Contacts Between Chalcogenide Glasses, Metals and Semiconductors

sponsored by the
Advanced Research Projects Agency
ARPA Order No. 1562

Semi-Annual Technical Report

Program Code No. 61101D
Contractor: Pennsylvania State University
Effective Date of Contract: June 1, 1970
Contract Expiration Date: May 31, 1971
Amount of Contract: $41,666.06

Contract No. DAHC0470C 0047
Principal Investigator: H. K. Henisch
Telephone: 814-865-1194

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The Director
Advanced Research Projects Agency
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Attention: Program Management

## Contacts Between Chalcogenide Glasses, Metals and Semiconductors

The two main purposes of the research here described are to elucidate the mechanism of threshold switching and to explore new device possibilities through the use of contact materials which can be electronically altered in situ.

During the first six months of the contract period the work has consisted of three parts: one concerned with glass film deposition on graphite and germanium substrates by flash evaporation and R. F. sputtering, one with pulse measurements on existing threshold switches and one with an exploration of switching delay statistics.

The new deposition facilities are in operation and have already been used for the preparation of threshold switching films. It has been shown that the use of n-type and p-type germanium substrates leads to interesting asymmetries. Somewhat surprisingly, these show themselves more in the ON-state than the OFF-state of the switches. As expected, they occur in opposite directions for n-type and p-type germanium contacts. These effects continue to be the subject of investigation. The results available to date demonstrate that (a) contact conditions *are* relevant to threshold switching (contrary to widespread popular belief), and (b) that the holding voltage of a threshold switch is *not* directly governed by the width of the mobility gap. Photoelectric measurements on such systems are planned for the near future. The necessary test jigs have already been designed and made.

Equipment has been set up which provides for digital read-out of the switching delay. It has been known for some time, that this delay is subject to a statistical variation, but the matter does not appear to have been properly investigated. It is important because the results must have a bearing on the final identification of the threshold switching mechanism. Similarly, any *change* in the mechanism, e.g. as between one temperature range and another, ought to show itself *inter alia* as a change in the statistical distribution of switching times and their relationship to overvoltage.

The pulse measurements on existing threshold switches (provided by Energy Conversion Devices, Inc.) have yielded a number of important results. These have been incorporated into two papers (concurrently submitted for publication) which form Appendices A and B of the present report. In brief, the results show that threshold switching (at any rate in ovonic devices) is not primarily a thermal process. They also provide evidence for a (previously predicted) space charge mechanism operative at low temperatures.

**APPENDIX A:** "Mechanism of Threshold Switching" by R. W. Pryor and H. K. Henisch.

**APPENDIX B:** "On the Mechanism of Ovonic Threshold Switching" by H. K. Henisch and R. W. Pryor.

# MECHANISM OF THRESHOLD SWITCHING

by

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In a recent communication, Balberg(1) has reported pulse measurements on chalcogenide glass threshold switches which show no polarization effects. The conclusion was that the double-injection space-charge mechanism(2, 3) is not operative, since space charges would render the system highly polarized in the immediate pre-threshold region. We have no reason to doubt these particular results, but it is important to correct the impression that they are generally valid for such systems. We find that polarization effects of the kind looked for by Balberg are indeed observed on 'Ovonic' threshold switches, occasionally (if not always) at room temperature and consistently at lower temperatures. In such measurements, excessive power dissipation (including that arising from a high repetition frequency) must be avoided since it tends to mask the polarization effects; so must excessively high over-voltages, since these establish their own operating regimes. The devices are most sensitive to their electronic history when the applied pulse amplitudes are in the neighborhood of (and, of course, slightly above) the threshold voltage. When the measurements are carried out under such conditions (at -78°C), polarization effects are observed as shown on Fig. 1. In Fig. 1(a) a voltage is applied and is seen to cause switching after a delay of 0.6 microseconds. This delay is independent of polarity. In Fig. 1(b) a pulse is reversed before it has had time to switch. The total time required for switching is then substantially longer (0.9 microsecond), in contrast to the behavior observed by Balberg who found the time unchanged. The longer the reversal is postponed, the greater is the lengthening of the switching delay. At room temperature the effects (in most of the switches available to the authors) are still measurable, but much smaller and close to the limit of experimental discrimination. The same is true if reversal takes place too early in the course of the pulse.

It is clear that the negative part of the pulse establishes conditions which are opposed to the final switching process. The behavior on Fig. 1 is in qualitative agreement with the double injection space charge model earlier advanced. This model is on quite general grounds more appropriate for low than for high temperatures, and the increase of polarity effects towards lower temperatures is therefore expected.

A comprehensive study of space charge effects and their interpretation will be published elsewhere(4). The measurements are best performed with pulse-pairs which are independently controlled as regards width, magnitude and timing. A demonstration of the fact that threshold switching is not essentially a thermal process has already been provided(5). The present results yield further confirmatory evidence, in as much as the 50% lengthening of the switching delay is evidently associated with a 50% increase in the total pre-switching energy dissipated in the system.

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This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by G. Boghosian, U. S. Army Research Office, Durham, under contract No. DAH CO4-70C. 0047. The authors also wish to thank S. R. Ovshinsky and S. Lee for their help.

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Figure Caption:

FIG. 1 Effect of Pulse Reversal on Threshold Switching.

(a) unidirectional pulse; switching delay 0. 6 microsecond.

(b) pulse reversal before switching; switching delay 0. 9 microsecond.

Vertical voltage scale: 10 volts per division.

Horizontal time scale: 0. 2 microseconds per division

Repetition rate: 100 Hz.

Temperature: -78°C.

Series load: 1K-ohms.

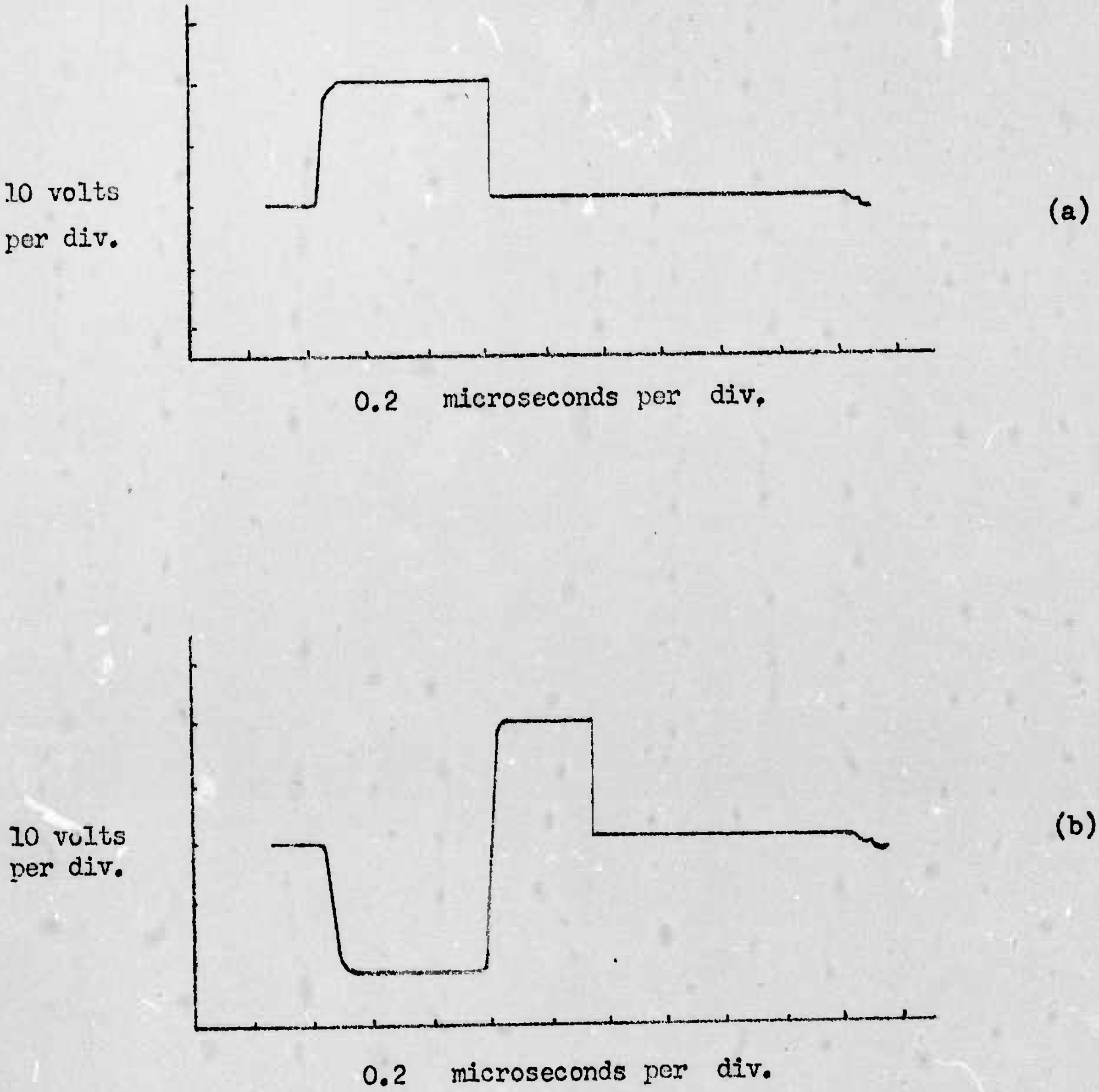

Figure 1. R. W. Pryor and H. K. Henisch

# ON THE MECHANISM OF OVONIC THRESHOLD SWITCHING

by

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## Abstract

By means of a "rare double pulse technique", it is shown that the mechanism of threshold switching in thin chalcogenide glass systems is essentially non-thermal in character. Polarization effects and polarization reversals on switching have been observed which are in qualitative harmony with a space charge theory of threshold switching previously advanced, at any rate in the low-temperature range. A non-polar electronic process is evidently operative above room temperature. The magnitude of the perturbation caused by heat dissipation in these systems is also assessed.

## Introduction

The mechanism of threshold switches (1) based on multicomponent chalcogenide glasses has for some time been a matter of controversy. The familiar switching characteristics are shown in Fig. 1a. A number of electronic processes have been proposed, e. g. space charge overlap (2, 3), field-assisted hopping (4) and impact avalanche formation (5, 6). On the other hand, several workers have held that threshold switching is a purely thermal phenomenon (7-13). There is also a compromise suggestion to the effect that it is an electronic process "thermally provoked" (14). Thermal theories envisage the sudden formation of a hot (and therefore highly conducting) filament as a result of power dissipation in the device. Because thermal breakdown is familiar and well understood, thermal theories of ovonic switching are at first sight among the most persuasive. Moreover, it has always been clear that some power is dissipated within the amorphous materials, and since these are highly temperature sensitive, the resulting heat is bound to have electrical consequences. The question was whether switching is itself such a consequence or whether thermal effects are superimposed on an essentially electronic mechanism. In this paper we shall provide evidence for the latter conclusion, and discuss also some of the requirements which any electronic interpretation of ovonic switching will have to satisfy. Having concluded that the switching process itself is not primarily thermal, it is then desirable to ascertain the nature and extent of the thermal contribution, and this is also done. The conclusions are in qualitative harmony with the space-charge model earlier advanced (3, 15), as far as the low temperature range is concerned. In the high temperature range (e.g. above room temperature) the trapping processes on which space-charge formation depends become increasingly inefficient, and other mechanisms tend to predominate.

The experiments here described were carried out on encapsulated switches* based on 1$\mu$ films of $Te_{40}As_{35}Ge_7Si_{18}$ between graphite electrodes. However, none of the observed properties are believed to be sensitively composition-dependent; the overall behavior is almost constant over a wide range of compositions and can therefore be discussed in general and non-specific terms. All the systems tested were highly symmetrical in their behavior. The temperature of the experiments is limited in the low range to about -90°C by the differential thermal contraction of the capsule. In the present series -78°C was the lowest temperature used. The high

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*Supplied by Energy Conversion Devices, Inc., through the courtesy of E. A. Fagen and R. Shaw.

range was limited to about 40°C, above which some of the switches showed small irreversible changes under the influence of unidirectional test pulses.

## Thermal Effects and Test Procedures

When a threshold switch is addressed by a continuous set of pulses, the average power dissipation can be varied in two ways: by varying the pulse length $t_o$ (in excess of the inherent switching delay) and by varying the repetition rage (Fig. 1b) and thereby the pulse interval $\tau$. The consequence of higher power dissipation is, of course, to produce an effective ambient which is higher than the external ambient temperature. The higher dissipation shows itself as a lowering of the minimum voltage required for threshold switching. This can be demonstrated by gradually increasing the pulse amplitude until switching is just obtained. Once this state is reached, the pulse amplitude can be lowered by an amount $\Delta V_{TH}$ while the periodic switching events continue. As long as the time interval between successive switching events exceeds about 1.2 microseconds, $\Delta V_{TH}$ appears to depend only on the average power dissipation. This is shown by Fig. 1c. The points correspond to various frequency and pulse length combinations but nevertheless form a smooth, self-consistent relationship. This is in agreement with results reported by Shanks (16) according to which the threshold voltage diminishes linearly with increasing ambient temperature. The clear implication is that, but for the power dissipation, the threshold voltage would be independent of frequency over the entire range (up to $\sim 8.10^5$Hz). When the energy per pulse is kept approximately constant, the decrease of $V_{TH}$ with increasing frequency is uniform. A small rise (e.g. 7-12°C) in the effective ambient temperature can account for the highest $\Delta V_{TH}$ values observed under such conditions. When the energy per switching operation is not constant (e.g. when the ON-period $t_o$ changes), very complicated relationships can result (see curve 3 on Fig. 3a), quite unsuitable for simple interpretation.

It follows that, if gross thermal effects are to be avoided, then pulse trains (or other signals) of high repetition frequency must not be used for test purposes. Instead, the switches must be addressed by pulses or, more conveniently, by pulse pairs (Fig. 2) which remain rare events, e. g. with repetition rates of the order of $10^2 - 10^1$Hz or less. $\tau$ can be varied, as can the amplitude of the A and B pulses. The average power dissipation can be made negligible; likewise the power dissipation of the B-pulse, since that pulse is turned off as soon as switching is observed. On the other hand, the total energy dissipated during the A-pulse can be varied in three ways: (i) by varying the ON-time $t_0$, (ii) by varying the series resistance and thereby the ON-current, and (iii) by varying the total applied voltage. Under each experimental condition, the amplitude of the B-pulse is slowly increased from zero until switching is just obtained. The voltage at which this happens depends, of course, on the chosen pulse width, but that can also be varied at will. The detailed behavior of the B-pulse can thus be examined as a function of the switching parameters of A and of the time elapsed since the A-pulse. If there is any electronic disequilibrium in the system after the cessation of the A-pulses, procedure (i) would not affect it, whereas (ii) and (iii) will do so. In this way, the consequences of heating and the consequences of electronic disequilibrium can in principle be differentiated. Moreover, the A- and B-pulses can be of different sign, which permits the investigation of polarity-dependent effects.

## Primary After-effects of Switching

Following the procedures described above, the two principal characteristics of the B-pulse (its minimum threshold voltage $V_{TH}$ and its switching delay $t_D$) have been measured as a function of $\tau$. Because switching delays are sensitive functions of overvoltage (applied voltages in excess of the minimum required for switching), great care must be taken to perform the $t_D$ measurements (Fig. 4b) under standardized conditions, i. e. at constant overvoltage, either in the sense of a constant ratio $V/V_{TH}$ or else a constant difference $V-V_{TH}$. Results for the second procedure are shown on Fig. 3. From a linear extrapolation towards smaller values of $\tau$, it is clear that the average power required to make $\Delta V_{TH}$ comparable with $V_{TH}$ would be three or four orders of magnitude higher than that actually employed. The large diminution of $V_{TH}$ observed at small values of $\tau$ would thus have to arise from some other mechanism. If, on the other hand, such an extrapolation were regarded as impermissible and if, accordingly, the sharp diminution of $V_{TH}$ were tentatively regarded as thermal, then the results on Fig. 3 would imply that the time constant of this process is of the order of 1 microsecond. The observed recovery period has been widely so interpreted: as the cooling time of a filamentary conductive channel, following the heat dissipation of the preceding pulse. Indeed, the existence of two time constants of very different magnitude has been predicted (17) on the basis of a simplified model, one governing the cooling of the filament itself and another governing the cooling of the surrounding device environment as a whole. The former should control the recovery of $V_{TH}$ after a previous switching process, the latter the recovery of $t_D$, since that depends on the effective ambient temperature at which the whole switching process is initiated. Figure 3 shows that such differences are not observed or, at any rate, not in the systems here examined. The implied time constants are the same. In practice, one would expect the temperature decay to be non-exponential, which is equivalent to a distribution of time constants. Judging from the results on Fig. 1, the longest of these must be of the order of a second or so; the shortest would appear to be much less than 0. 6 $\mu$ sec (see below).

Measurements of the kind shown in Fig. 3 can be carried out for various values of $t_o$ and A-current. Corresponding values for $V_{TH}$ are given in Fig. 4, for an arbitrary and constant value of $\tau$ within the critical decay period. Similar observations have been made after other (longer) decay times. Since the range of $t_o$ values is also well within the small time constant implied by Fig. 3a, the results on Fig. 4a show that the minimum threshold voltage remains (within the accuracy here involved) unaffected by the energy dissipated during the A-pulse. This is further confirmed by Figs. 4b and 4c. That the filament is at a somewhat elevated temperature while it exists cannot be doubted. However, the results on Fig. 1 suggest strongly that the heating effects are quite small, and those on Fig. 4 show that they have already decayed after 0.6 microseconds. The B-pulse 'remembers' the previous switching process and reacts to it by lowering its threshold voltage, but it is not the temperature reached during the previous event which governs its behavior. The only plausible conclusion is that the after-effects of switching are electronic in character and that they show themselves during the time necessary for a return to electronic equilibrium. Note also (insert in Fig. 3a) that the threshold voltage does not diminish to zero as $\tau$ diminishes, but to the holding voltage $V_H$ (see Fig. 1a). This has been independently observed by R. Shaw (18). The present interpretation is, of course, based on the assumption that an increase of energy dissipation makes the system hotter. It would be possible, in principle, to envisage subtle plasmas in which this is not the case [we are indebted to Professor R. Grigorovici for this suggestion], but there is no independent evidence of their existence here.

The conventional voltage-current characteristic is a relationship obtained under conditions which imply a long delay between the ON-state and the subsequent OFF-state. As the delay is diminished there is, in accordance with the above, little change until times of the order of 1 microsecond or less are involved. For smaller values of $\tau$, $V_{TH}$ diminishes sharply as shown on Fig. 3, and a hitherto unanswered question relates to the behavior of the threshold current under these conditions. Measurements with non-switching B-pulses, following switching A-pulses after a suitable time delay, show that the system behaves as shown in Fig. 5. Each of the broken lines refers to a form of transient OFF-characteristic, associated with a definite value of $\tau$. A switching pulse thus affects not only the threshold voltage of a subsequent switching event, but also its pre-switching current, as one would expect.

## Polarity and Temperature Dependent After-effects of Switching Pulses

It is of interest to examine how a B-pulse reacts to a switching A-pulse of opposite polarity. This is shown in Fig. 6. At room temperature, the difference between positive and negative A-pulses is small in some units, undetected in others (as on Fig. 6a); at -78°C it is pronounced in all cases. The minimum threshold voltage of B is lowered when the previous switching pulse is of opposite polarity. In a similar way, the polarity of the switching A-pulse can be shown to affect the pre-threshold current of subsequent events. That is why the broken lines in Fig. 5 appear in pairs. The significance of these results and the slow decay of the voltage differences with time will be further discussed below. Meanwhile, it may be noted that room temperature is approximately the boundary between conditions under which polarity effects are prominent and those under which they are negligible. The boundary is necessarily unsharp; for different units the change-over occurs at somewhat different temperatures.

## Polarity and Temperature Dependent After-effects of Pre-switching Pulses

Measurements can also be made with A-pulses which are in the pre-threshold region, i. e. which are insufficient to cause threshold switching.

The effect is smaller than that caused by A-pulses which exceed threshold and, in order to detect it, the pulse interval $\tau$ is best reduced to zero. Figure 7 gives a typical trace, and Fig. 8 shows corresponding results obtained at three temperatures. In Fig. 8a, $(V_{TH})_B$ is plotted against the corresponding values of the switching delay $(t_D)_B$ for zero A-pulse (as a reference line) and for pre-switching A-pulses of the same and of opposite polarity (see Fig. 2b). After-effects which could be interpreted as Peltier heating have not been observed. In the circumstances, the polarity sensitive effects cannot conceivably be thermal. Again they are more prominent at low than at high temperatures, as expected. The direction of this polarity-dependence is, however, reversed compared with that shown in Fig. 6; the after-effects of a switching pulse and those of a non-switching (pre-threshold) pulse are of opposite sign. This can be understood in terms of the space-charge model previously advanced (3, 15) or some simple variant of it, because this model envisages space-charge development before the onset of the switching process and a reversal of its polarity by the act of switching (see below).

Oscillographic records of the kind shown on Fig. 7a can be challenged on the grounds that the device may not "see" the B-pulse for the same length of time in the two cases, because a voltage reversal necessitates the recharging of device and threshold capacitances. (We are indebted to H. Fritzsche for pointing this out.) There are, however, three sets of confirmatory results which show that the present conclusions are genuine and do not arise from timing uncertainties of this kind.

(a) Measurements of the type shown on Fig. 7a can be modified so as to keep the $(V_{TH})_B$ values constant. This necessitates a widening of the B-pulse after a negative A-pulse, from the original 0.2 $\mu$sec. to 0.4 $\mu$sec. Figure 7b shows this. It is obvious that such an interval is far outside the range of any plausible timing uncertainty.

(b) The observed polarity effects are dependent on the duration of the pre-switching A-pulses, as shown on Fig. 9a.

(c) The observed polarity effects do not disappear with increasing B-pulse duration, as would be expected if they were due to timing uncertainties.

The reality of the effects illustrated on Figs. 7 and 8 cannot therefore be in doubt.

Power dissipation in the specimens affects these relationships (Fig. 8) in a sensitive way. This can be demonstrated by simply increasing the repetition rate of the A-B pulse-pair. As a result, the polarity effects tend to vanish, as shown in Fig. 10. The power-dissipation here involved is, of course, mainly that of the pre-switching A-pulse. Though the pre-switching currents are low, the applied voltages are high and the total energy dissipated during a (say) 8$\mu$sec pre-switching pulse (as actually used) is in fact comparable with that of a (say) 0.5$\mu$sec switching pulse. The corresponding temperature distributions will, of course, be very different, because filament formation during the A-pulse is not involved if that pulse is in the pre-threshold region. In any event, the results on Fig. 8 refer to $\tau = 0$ which renders them much more sensitive to residual temperature effects than those on Fig. 3, which refer to $\tau = 0.6\mu$sec.

The after-effects of pre-threshold A-pulses must obviously depend also on the magnitude of the applied voltage. A typical relationship for a constant A-pulse width is shown on Fig. 9b. The slope at $V_A = 0$ varies somewhat from switch to switch, but the sign is always the same and so is the saturation effect with increasing A-voltage. The fact that a non-zero slope exists at $V_A = 0$ is itself significant, since the power dissipation obviously tends to zero in this region. Nevertheless, the switch is being "prepared for breakdown", evidently in a non-thermal manner. Carrier injection provides a plausible interpretation.

Results of the kind here reported (Figs. 7 and 8) are in apparent but not real conflict with those of Shanks (16), who found no clear evidence for polarity effects at room temperature. For some switches, the present results confirm this. In other cases, residual polarity effects have been observed during the present work. It is now known that these disappear rapidly as the specimen temperature goes up. It can do so either through a change of ambient temperature or else through a high internal power dissipation. The polarity effects also become too small to be measured with any degree of reliability if the A-pulse voltage is far below the threshold voltage. The latter situation is likely to have prevailed in Shanks' experiments. In a similar way, Balberg (19) has reported room temperature measurements involving simple pulse-reversals before switching which show only symmetrical behavior. Corresponding low temperature measurements performed in the course of the present work (20) are shown on Fig. 11. Some switches (but not all) showed similar but smaller polarity effects even at room temperature. The longer the reversal is postponed, the greater is the lengthening of the corresponding switching delay. The results are a further demonstration of the fact (15) that the switching process is essentially non-thermal, inasmuch as a 50% lengthening of the switching delay is here evidently associated with a 50% increase in the total pre-switching energy dissipated in the system.

As Figs. 7, 8 and 9b show, a pre-switching pulse in the same direction as the final switching pulse helps to create the conditions necessary for reaching the threshold point. A pre-switching pulse in the opposite direction impedes their creation. The space charges which such a pulse creates (see below) must evidently be destroyed before switching in the opposite direction can take place; hence the longer switching delay $t_D$. The polarization effects are seen to linger over periods of time which are a good deal longer than the lifetime of free carriers, as inferred from the speed of photoconductive delay.

This is easily understood, since we are here dealing not with free carriers but with a residual occupation of deep carrier traps.

## Evidence for a Low Temperature Space Charge Mechanism

Certain side effects have been identified as thermal but the experiments here reported show that ovonic threshold switching is essentially a non-thermal process. The conclusion is that one or more electronic mechanisms are at work, and this is further re-inforced by the results of recent observations on ovonic memory switching (21). Electronic mechanisms may be polar or non-polar, and the present results show that both types prevail. A non-polar mechanism evidently prevails at high temperatures (above room temperature) and polar one at low temperatures. The chalcogenide glasses on which threshold switches are based are known to exhibit space-charge controlled photoconductive effects at low temperature (3) and to support the formation of electrets (22), even at room temperature. Both processes imply the existence of deep carrier traps, and this feature is in harmony with the overlapping band models which have been devised for amorphous semiconductors on quite different grounds (electrical and optical). Deep traps, in turn, imply space charges, except under very special conditions (believed to exist at the threshold point) under which complete mutual neutralization of electron and hole traps is possible. A space charge model previously proposed (3, 15) envisages polarization and space charge reversals in the course of threshold switching. These relationships are represented on Fig. 12. They are qualitatively substantiated by the experiments described above. This does not necessarily mean that the simplest space charge theory of threshold switching will prove to be satisfactory in every detail, but it does provide prima facie evidence of its basic validity, at any rate in the low temperature range. Above room temperature, trapping becomes inefficient and other (non-space charge) processes are likely to make their influence felt. Switching measurements reported by Fritzsche (23) tend to substantiate the existence of two temperature ranges, distinct but with a smooth change-over from one to the other. At high temperatures, the switching point is approached with increasing voltage after passing through a pre-threshold regime which is almost ohmic; at low temperatures it is grossly non-ohmic (Fig. 13). The continuity itself is not surprising if one accepts the central premise: that the threshold point represents the condition under which electron traps are full of electrons (to the extent to which the prevailing temperature allows) and hole traps full of holes, the assembly being locally neutral everywhere. Under these conditions, additional carriers entering through the electrodes would pass through the amorphous material untrapped, and the conductance would therefore be high.

The precise mechanism whereby the switching condition is achieved is expected to be unimportant for what follows, i. e. for the factors governing the ON-state. In the low temperature range, neutralization can come about by the overlap of two opposing space charges, growing out of the anode and cathode respectively. At higher temperatures, the space charges are evidently screened out, and other mechanisms which lead to non-equilibrium trap filling must come into play. One such is field-assisted hopping, as proposed by Fritzsche (4) and another impact avalanche formation, as proposed by Hindley (5) and Mott (6). Avalanche theories will have to cope with the fact that the threshold voltage tends to zero as the ambient temperature tends to about 170°C (16), a fact not easily reconciled with the need for a critical breakdown field. A conclusive identification of the high temperature switching mechanism has not yet been possible. The fact that the polarization effects here reported, though distinctly measurable, are small, suggests that the space charge mechanism is not in exclusive control even at low temperatures, but is operative as a significant factor in promoting the threshold switching condition.

## Nature of the ON-current

Whatever the mechanism of trap filling and space-charge neutralization, the ON-state of the switch must be envisaged as a gross electronic disequilibrium, maintained by the current density against the prevailing recombination processes which tend to restore equilibrium. The existence of a minimum holding current can be readily explained in these terms. However, the results on Fig. 4b call for additional comment. In the ordinary way, one would expect an increase of current density to imply an increased departure from equilibrium, whereas the measurements demonstrate the constancy of $(V_{TH})_B$ with changing A-current. This is capable of a simple explanation. There is independent evidence that the ON-current is filamentary in character. This is a compelling inference from the fact that ON-currents are independent of electrode area. Filament formation may be thermally initiated or may be controlled by plasma considerations. It is thus plausible to suppose that the diameter of the ON-state filament increases in such a way as to keep the current density at least approximately constant. As far as the degree of electronic disequilibrium is concerned, all ON-currents would then be equivalent, at any rate within the limits so far explored. The results on Fig. 6 show that the decay rate of this disequilibrium is virtually temperature independent between -78°C and room temperature.

Since ON-state and OFF-state are believed to differ grossly as far as the trapped carrier concentrations are concerned, it is also plausible that the effective carrier mobilities may be different in the two cases. However, no experimental technique has been devised so far which is capable of making this assessment.

## General Considerations

Recognition of the non-thermal character of threshold switching provides new incentive for this type of research, and until the mechanisms involved have been qualitatively recognized beyond reasonable doubt, mathematical model making is bound to be unrewarding. Quantitative models must, in any event, take account of the fact that, in the materials concerned, the dielectric relaxation time is long compared with the lifetime of non-equilibrium carriers. Van Roosbroeck and Casey (24) have recently shown that trapping effects quite different from those found in normal (crystalline) semiconductors may be expected under these conditions. Such considerations are bound to play a role in the analysis of the threshold switching mechanism. They affect the problem of screening under dynamic conditions, and in particular, the detailed mechanism whereby space charges can be sustained in the presence of intermingled hole- and electron traps in high concentrations. The general prediction is that extensive space charges can be created under such conditions. The problem is also eased by Fritzsche's recently compiled evidence that electrons and hole traps are not completely intermingled but are spacially separated to a certain extent (25), and therefore less in communication with one another than was at one time believed.

The conclusions here reached in no way deny that a thermal form of threshold switching may take place in other types of systems, and possibly even in chalcogenide glass films of much greater thickness (e.g. $>10\mu$), than here used. Whether such films of greater thickness actually do switch thermally or electronically is still open to doubt. Fritzsche and Ovshinsky (26) have shown that the switching behavior in such cases is not incompatible with thermal interpretations. On the other hand, the switching characteristics of thick films are remarkably similar to those of thin films, as far as voltage-current characteristics are concerned. The matter is in need of further study. As the detailed properties of threshold switches become known, the interpretational options become more restricted and the switching mechanism correspondingly clearer.

## Acknowledgements

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by G. Boghosian, U. S. Army Research Office, Durham, under contract No. DAHC0470 C 0047. The authors also wish to thank H. Fritzsche, R. Grigorovici, Sir Nevill Mott, S. R. Ovshinsky and R. Shaw for extensive discussions.

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## FIGURE CAPTIONS

Fig. 1. Measurements with uniform pulse trains.

(a) normal threshold switching characteristics.

(b) pulse parameters; substantial energy dissipation confined to interval $t_o$.

(c) reduction of threshold voltage for various average power dissipations.

Fig. 2. The 'rare' double pulse technique.

(a) arrangement of pulse generators and switching unit (OTS). Generator type: EH 132 A-8.

(b) pulse parameters; B-pulse raised from zero until switching just occurs. Substantial energy dissipation confined to interval $t_o$.

Fig. 3. Measurements by the 'rare' double pulse technique.

(a) Threshold voltage $(V_{TH})_B$ as a function of pulse interval $\tau$.

1 constant energy per A-pulse

2 zero energy per A-pulse (extrapolated)

3 non-constant energy per A-pulse, arising from simple variation of frequency

(b) Switching delay $(t_D)_B$ as a function of pulse interval $\tau$, measured at a constant overvoltage of 1 volt.

A - pulse switching parameters:

$(t_D)_A = 1 \mu$ sec $\quad (t_o)_A = 1 \mu$ sec

$V_A = 13$ volts

B - pulse parameters: total width: $2 \mu s$; height: variable

Series resistance: 3. 3 K-ohms.

Fig. 4. Threshold voltage of B-pulse as a function of A-pulse switching parameters.

(a) $(V_{TH})_B$ versus $t_o$ for $\tau = 0.6\mu s$ and $(t_D)_B = 0.6\mu s$, ON-current (A): 4 values as stated.

(b) $(V_{TH})_B$ versus ON-current (A) for $\tau = 0.6\mu s$, $(t_D)_B = 2\mu S$ and $t_o = 0.5\mu s$.

(c) $(V_{TH})_B$ versus power and energy of the A-pulse for $t_o = 0.5\mu s$, $\tau = 0.6\mu s$ and $(t_D)_B = 2\mu s$.

Room temperature ambient.

Fig. 5. Schematic representation of transient V-I threshold characteristics, for different times $\tau$ after switching A-pulses.

Fig. 6. Effect of the polarity of a switching A-pulse on the threshold voltage of a subsequent B-pulse.

(a) room temperature.

(b) low temperature.

Fig. 7. Effect of non-switching A-pulses on subsequent B-pulses.

(a) constant $(t_D)_B$

(b) constant voltage

T = 195°K.

Fig. 8. Effect of non-switching A-pulses on the switching parameters $V_{TH}$ and $t_D$ of subsequent B-pulses. $\tau = 0$.

A - pulse duration: 8 microseconds.

A - pulse amplitude: ~ 1 volt below threshold at each temperature.

Fig. 9. Effect of non-switching A-pulses on the threshold voltage of subsequent B-pulses. T = 195°K.

(a) and (b): $(t_D)_B = 0.2$ microseconds, series R = 1000 ohms;

(b) length of A - pulse = 8 microseconds.

Fig. 10. Effect of internal power dissipation on switching asymmetry. Non-switching A-pulses of equal or opposed polarity.

A - pulse: 8 microseconds, 19.4V, R = 1000 ohms.

Fig. 11. Effect of pulse reversal on threshold switching.

(a) unidirectional pulse; switching delay 0.6 microseconds.

(b) pulse reversal before switching; switching delay of 0.9 microseconds.

T = 195°K, R = 1000 ohms.

Fig. 12. Space charge reversal in the course of threshold switching [After (3)].

Fig. 13. Conductance of a 0.8 $\mu$m thick chalcogenide glass alloy as a function of applied voltage [After Fritzsche (23)].

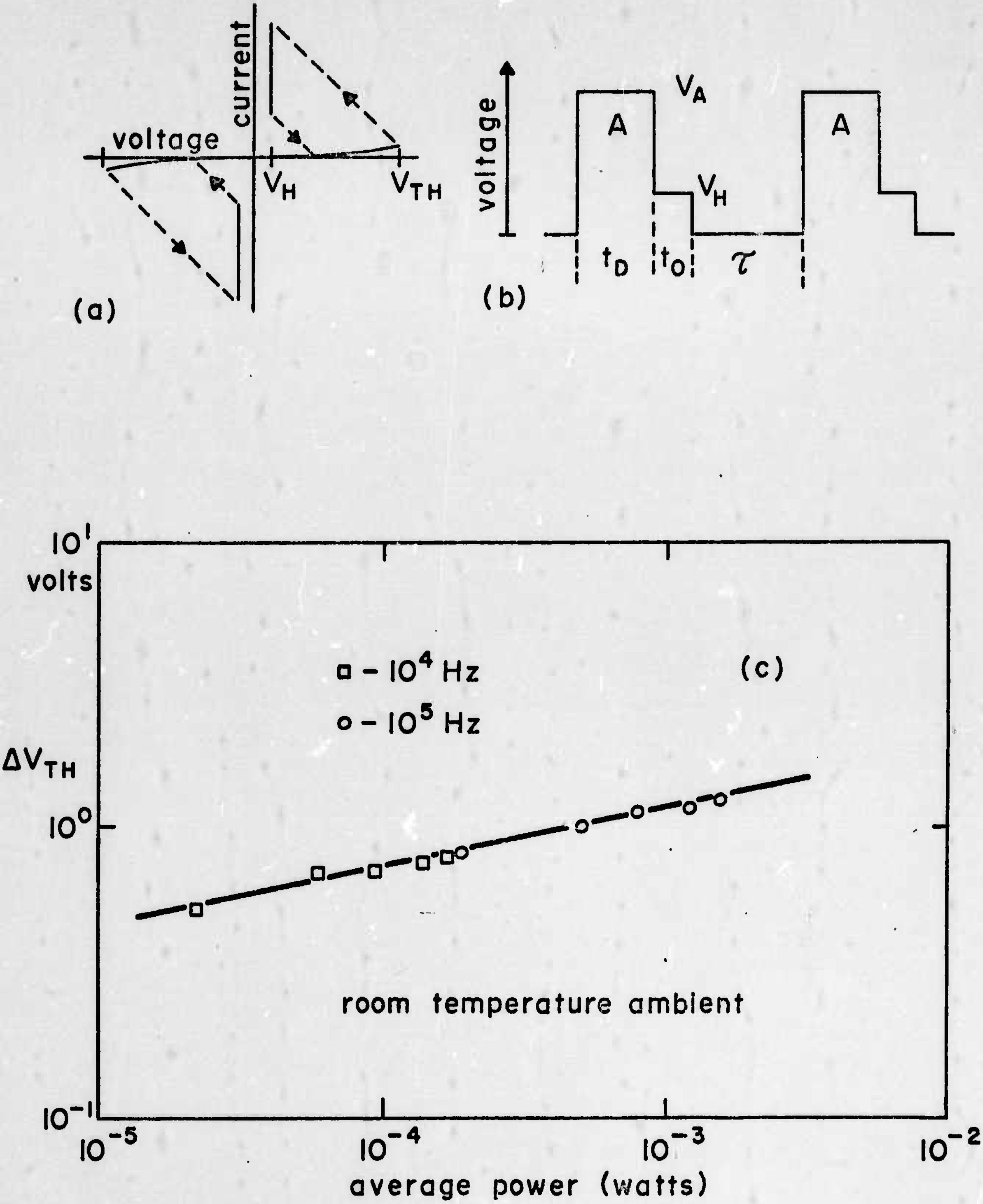

current
voltage
$V_H$
$V_{TH}$
(a)
voltage
$V_A$
A
A
$V_H$
$t_D$
$t_0$
$\tau$
(b)
$10^1$ volts
$\Delta V_{TH}$
$10^0$
$10^{-1}$
□ - $10^4$ Hz
○ - $10^5$ Hz
(c)
room temperature ambient
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
average power (watts)

Fig. 1

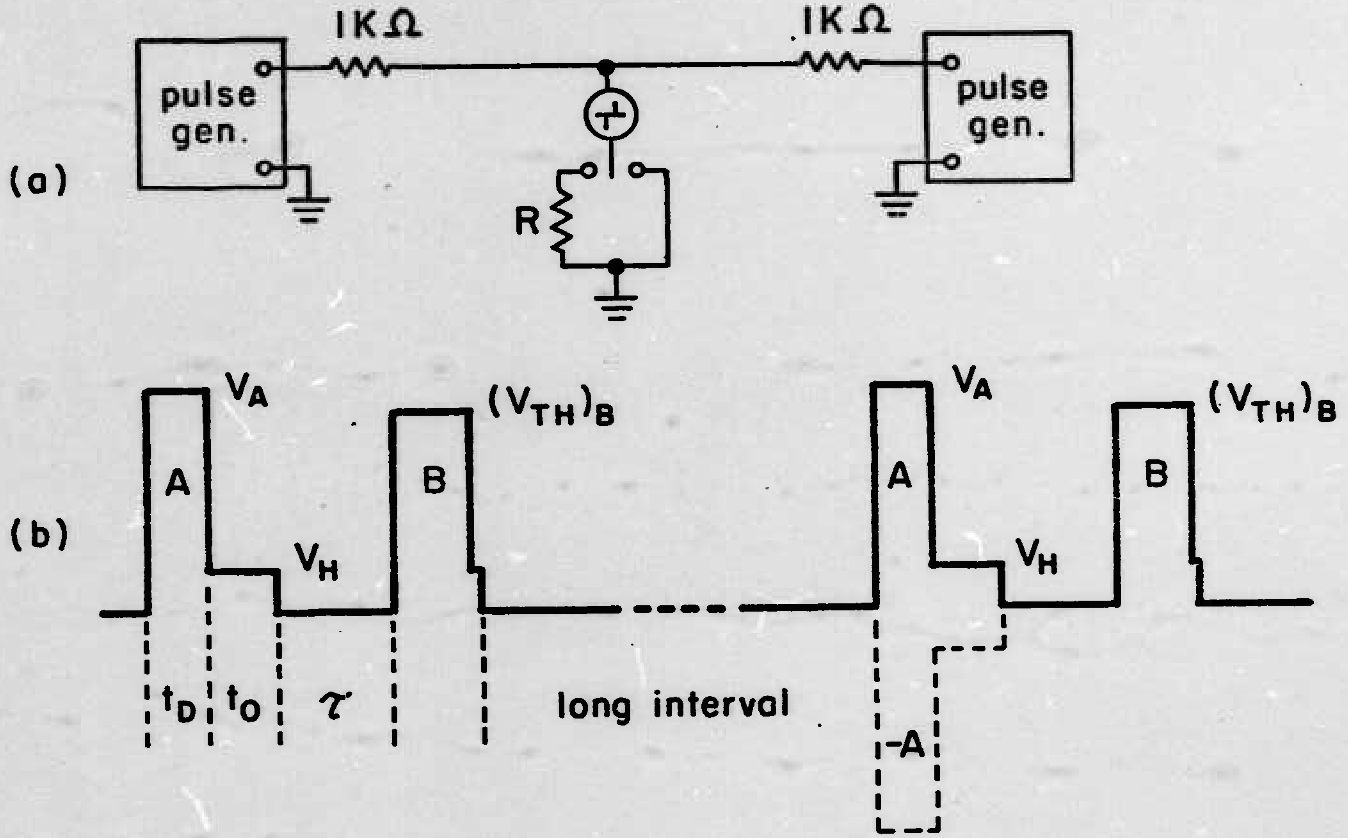

(a)
pulse gen.
1KΩ
R
1KΩ
pulse gen.
(b)
A
$V_A$
$V_H$
B
$(V_{TH})_B$
$t_D$
$t_0$
$\tau$
long interval
A
$V_A$
$V_H$
-A
B
$(V_{TH})_B$

Fig. 2

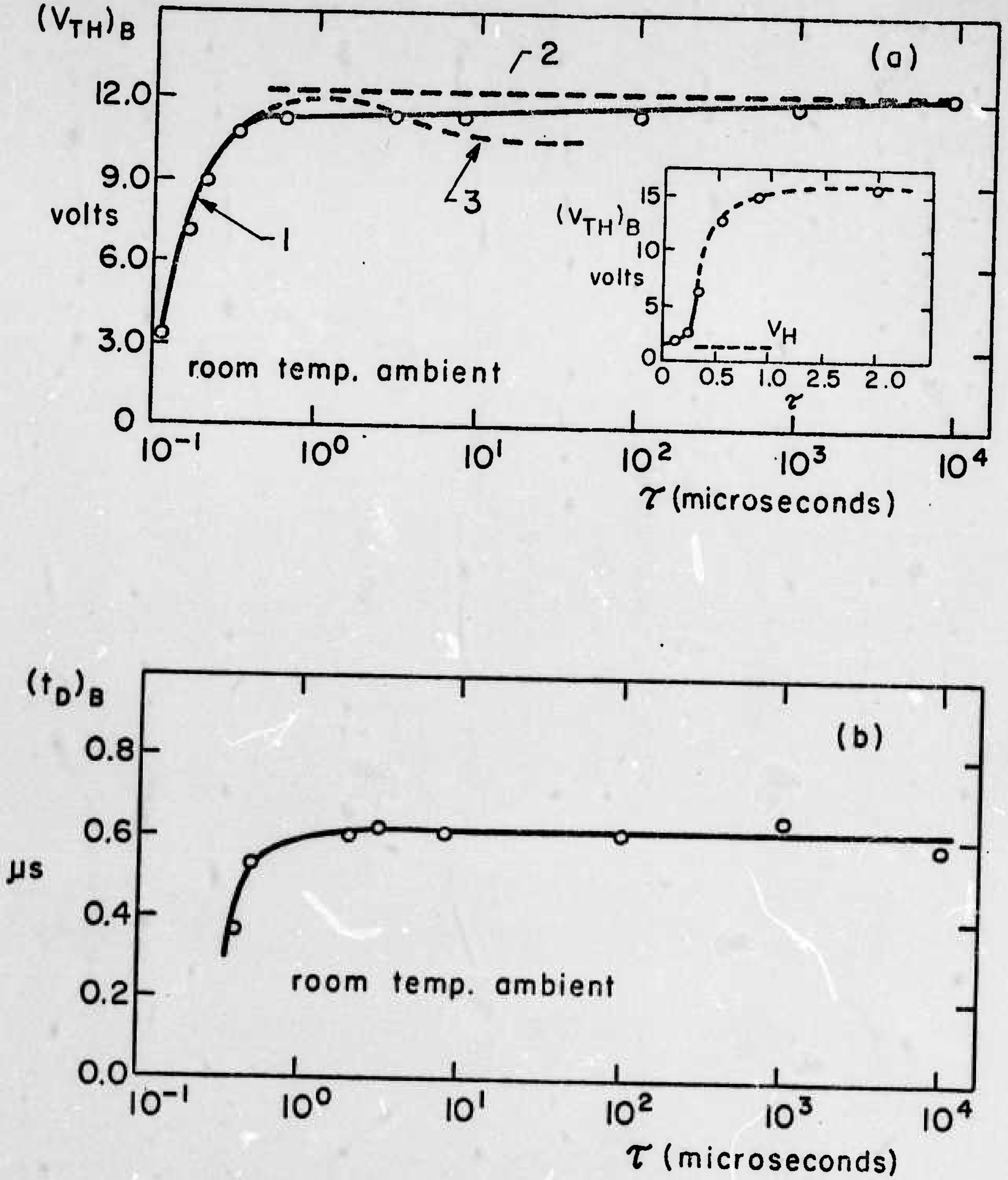

(a)
$(V_{TH})_B$
volts
12.0
9.0
6.0
3.0
0
1
2
3
room temp. ambient
$10^{-1}$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$\tau$ (microseconds)
$(V_{TH})_B$
volts
15
10
5
0
$V_H$
0
0.5
1.0
2.5
2.0
$\tau$
(b)
$(t_D)_B$
μs
0.8
0.6
0.4
0.2
0.0
room temp. ambient
$10^{-1}$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$\tau$ (microseconds)

Fig. 3

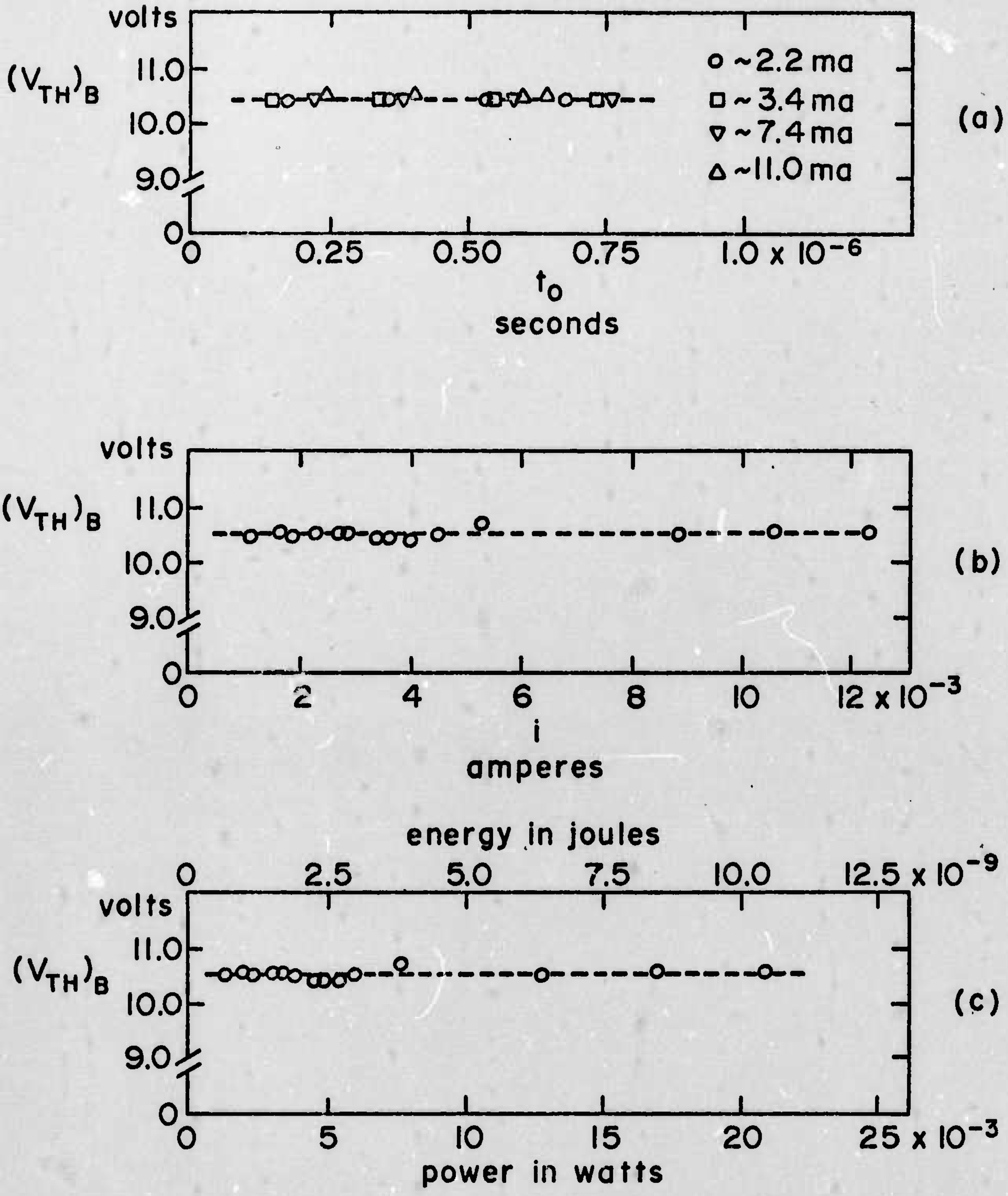
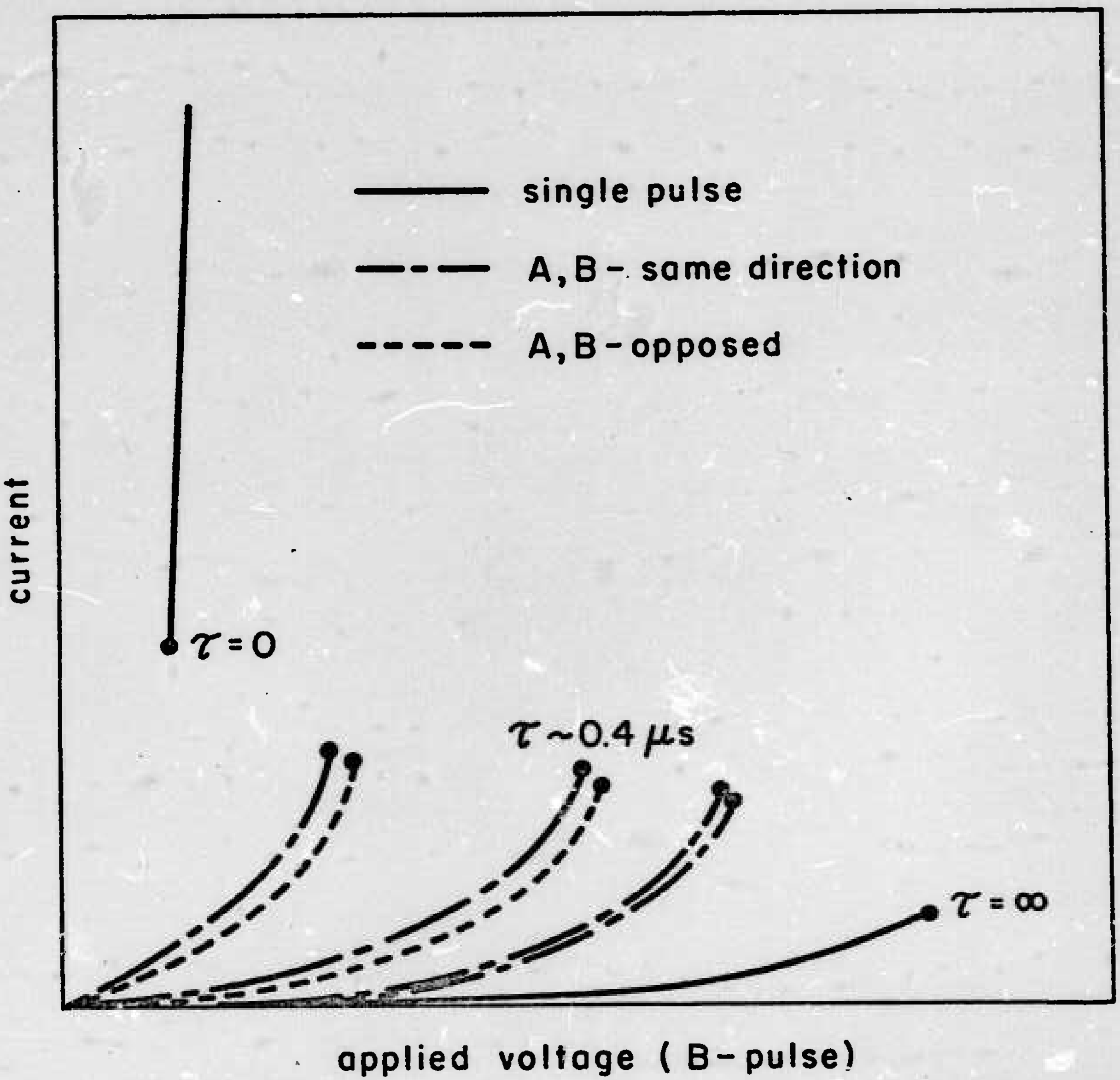

volts
$(V_{TH})_B$
11.0
10.0
9.0
0
○ ~2.2 ma
□ ~3.4 ma
▽ ~7.4 ma
△ ~11.0 ma
(a)
0
0.25
0.50
0.75
1.0 x $10^{-6}$
$t_o$
seconds
volts
$(V_{TH})_B$
11.0
10.0
9.0
0
(b)
0
2
4
6
8
10
12 x $10^{-3}$
i
amperes
energy in joules
0
2.5
5.0
7.5
10.0
12.5 x $10^{-9}$
volts
$(V_{TH})_B$
11.0
10.0
9.0
0
(c)
0
5
10
15
20
25 x $10^{-3}$
power in watts

Fig. 4


single pulse
A, B - same direction
A, B - opposed
current
$\tau = 0$
$\tau \sim 0.4\ \mu s$
$\tau = \infty$
applied voltage ( B-pulse)

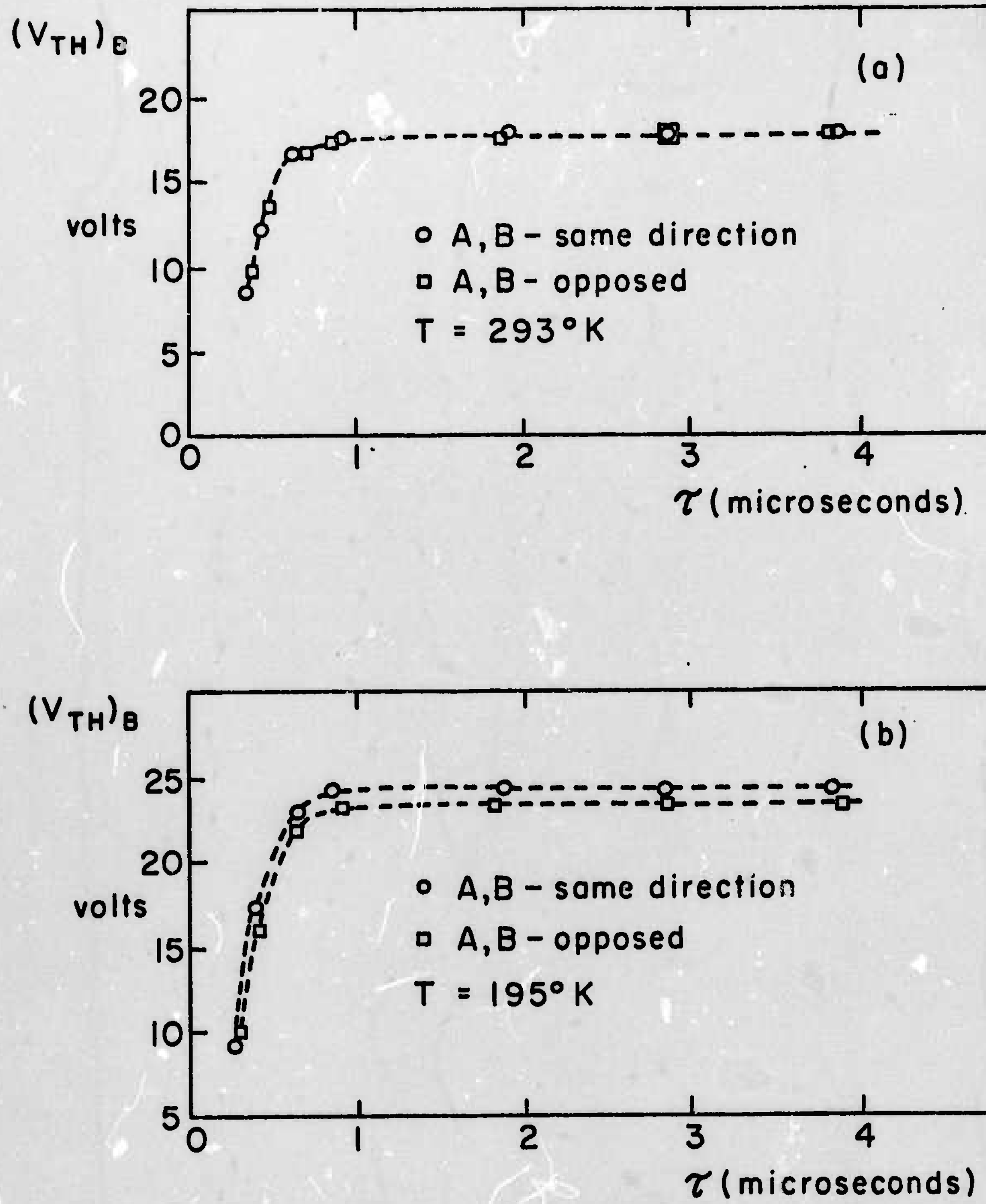

(a)
$(V_{TH})_B$
volts
0
5
10
15
20
0
1
2
3
4
$\tau$ (microseconds)
○ A, B - same direction
□ A, B - opposed
T = 293° K
(b)
$(V_{TH})_B$
volts
5
10
15
20
25
0
1
2
3
4
$\tau$ (microseconds)
○ A, B - same direction
□ A, B - opposed
T = 195° K

Fig. 6

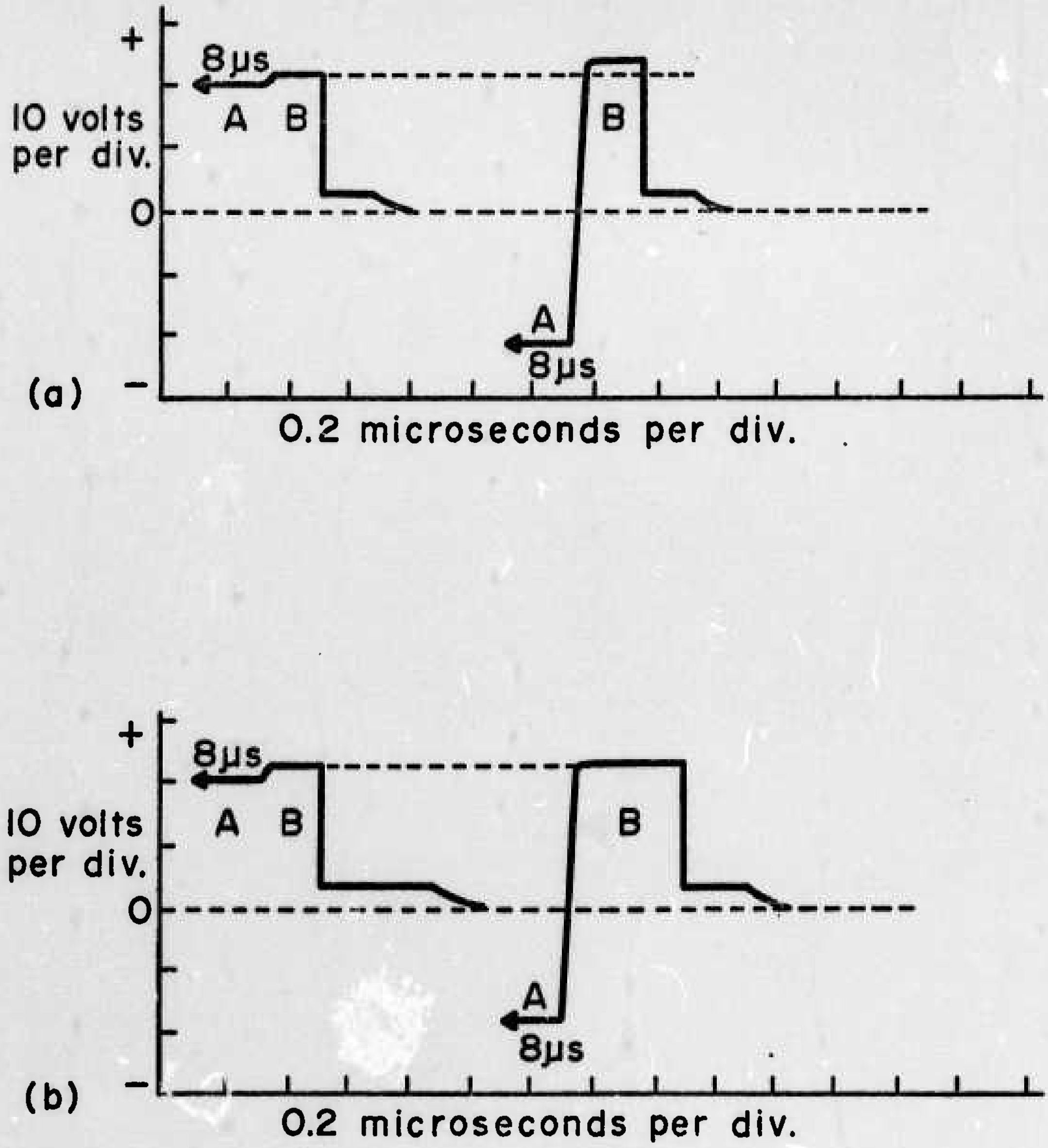

+
8µs
A
B
10 volts
per div.
O
A
8µs
B
(a)
−
0.2 microseconds per div.
+
8µs
A
B
10 volts
per div.
O
A
8µs
B
(b)
−
0.2 microseconds per div.

Fig. 7

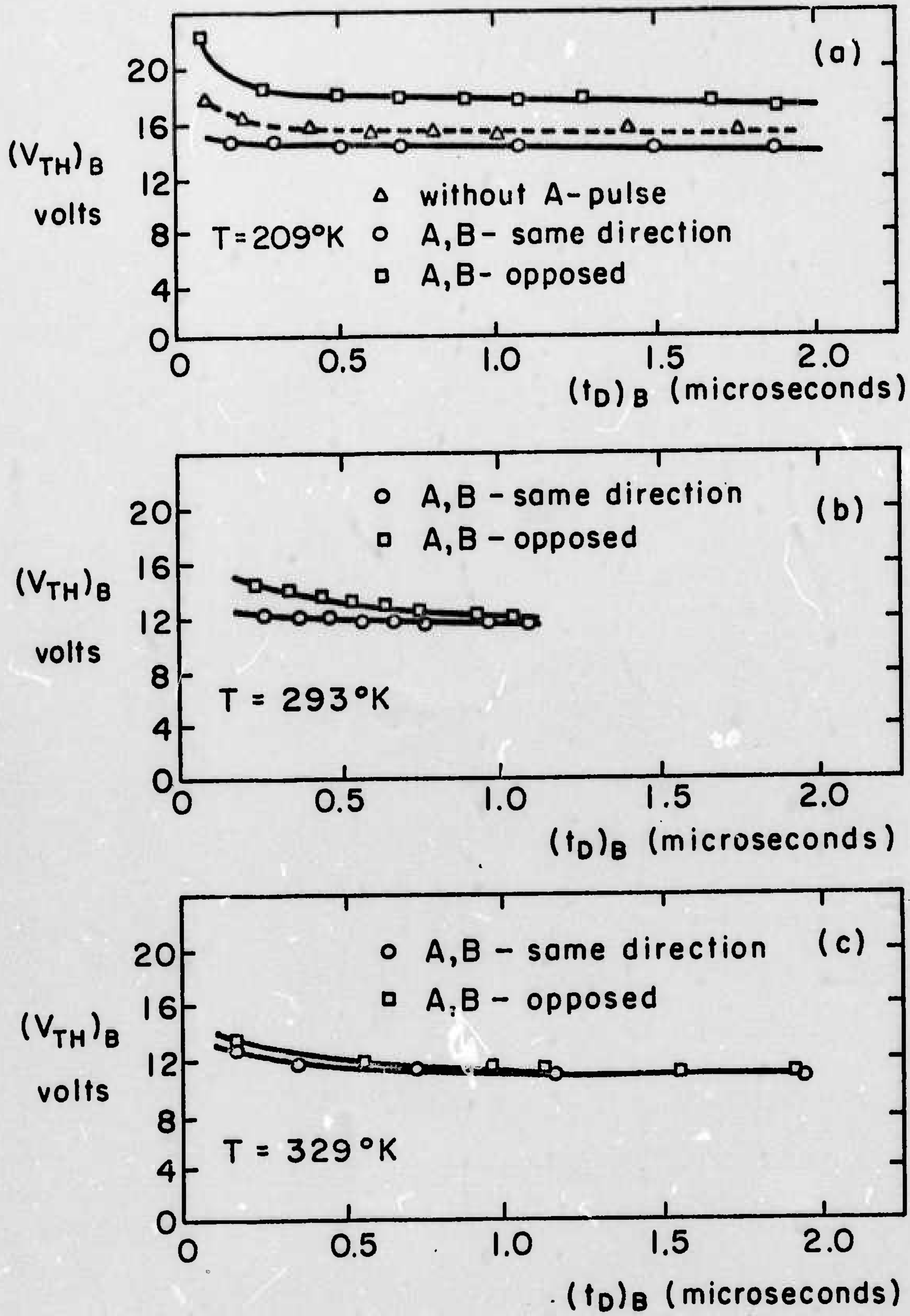

(a)
(V_TH)_B volts
0
4
8
12
16
20
T=209°K
△ without A-pulse
○ A,B- same direction
□ A,B- opposed
0
0.5
1.0
1.5
2.0
(t_D)_B (microseconds)
(b)
(V_TH)_B volts
○ A,B - same direction
□ A,B - opposed
T = 293°K
(t_D)_B (microseconds)
(c)
(V_TH)_B volts
○ A,B - same direction
□ A,B - opposed
T = 329 °K
(t_D)_B (microseconds)

Fig.

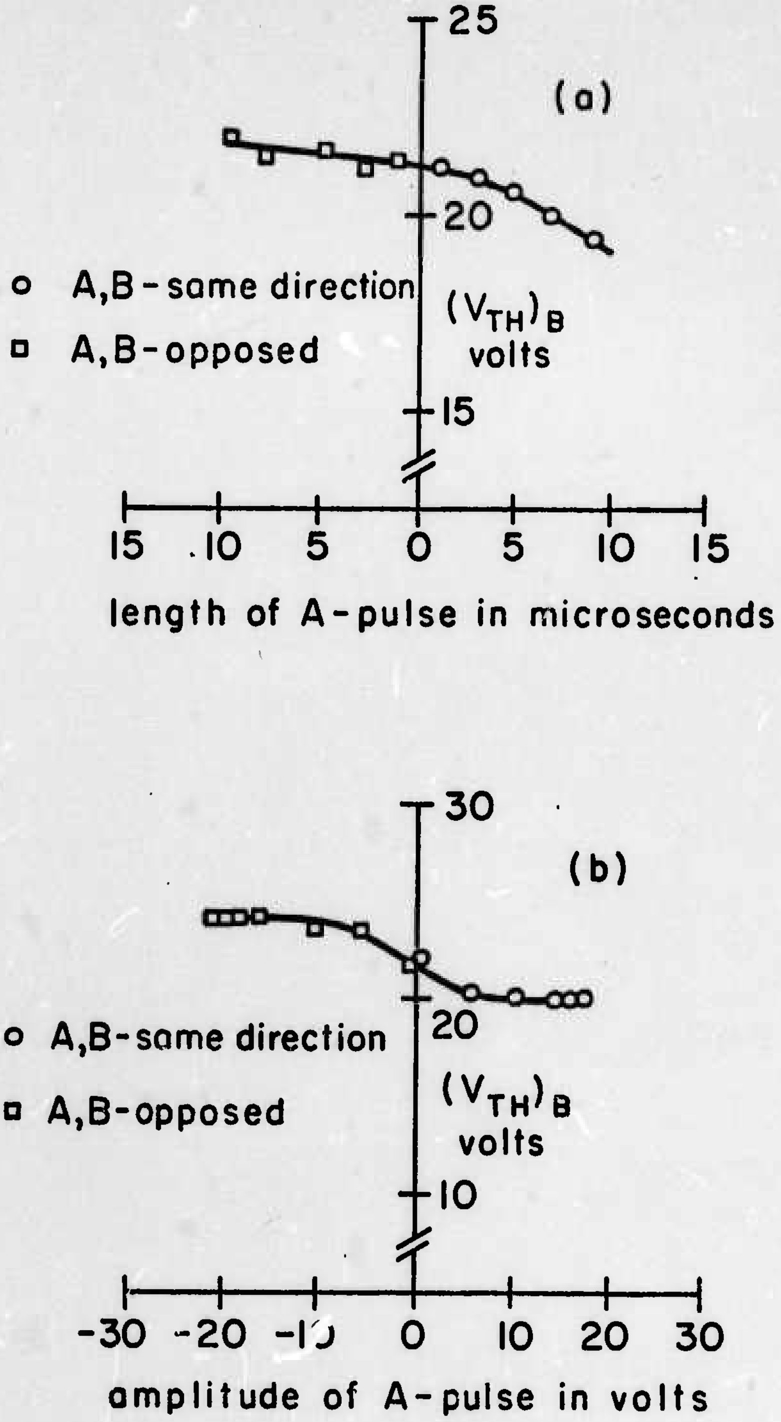

25
(a)
20
○ A,B - same direction
□ A,B - opposed
$(V_{TH})_B$
volts
15
15
10
5
0
5
10
15
length of A - pulse in microseconds
30
(b)
20
○ A,B - same direction
□ A,B - opposed
$(V_{TH})_B$
volts
10
-30
-20
-10
0
10
20
30
amplitude of A - pulse in volts

Fig. 9

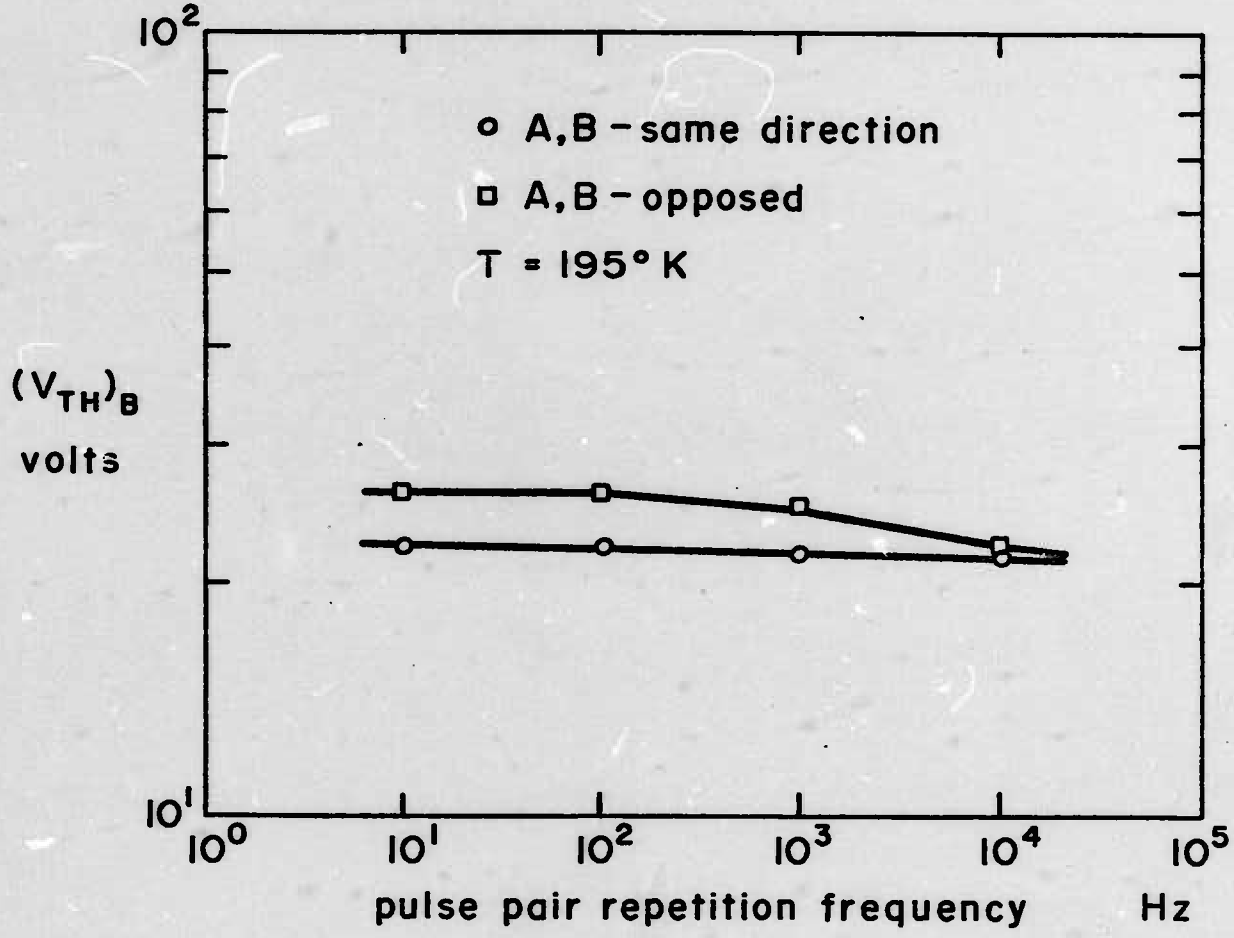

$10^2$
$10^1$
$(V_{TH})_B$
volts
○ A,B - same direction
□ A,B - opposed
T = 195° K
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
pulse pair repetition frequency
Hz

Fig. 10

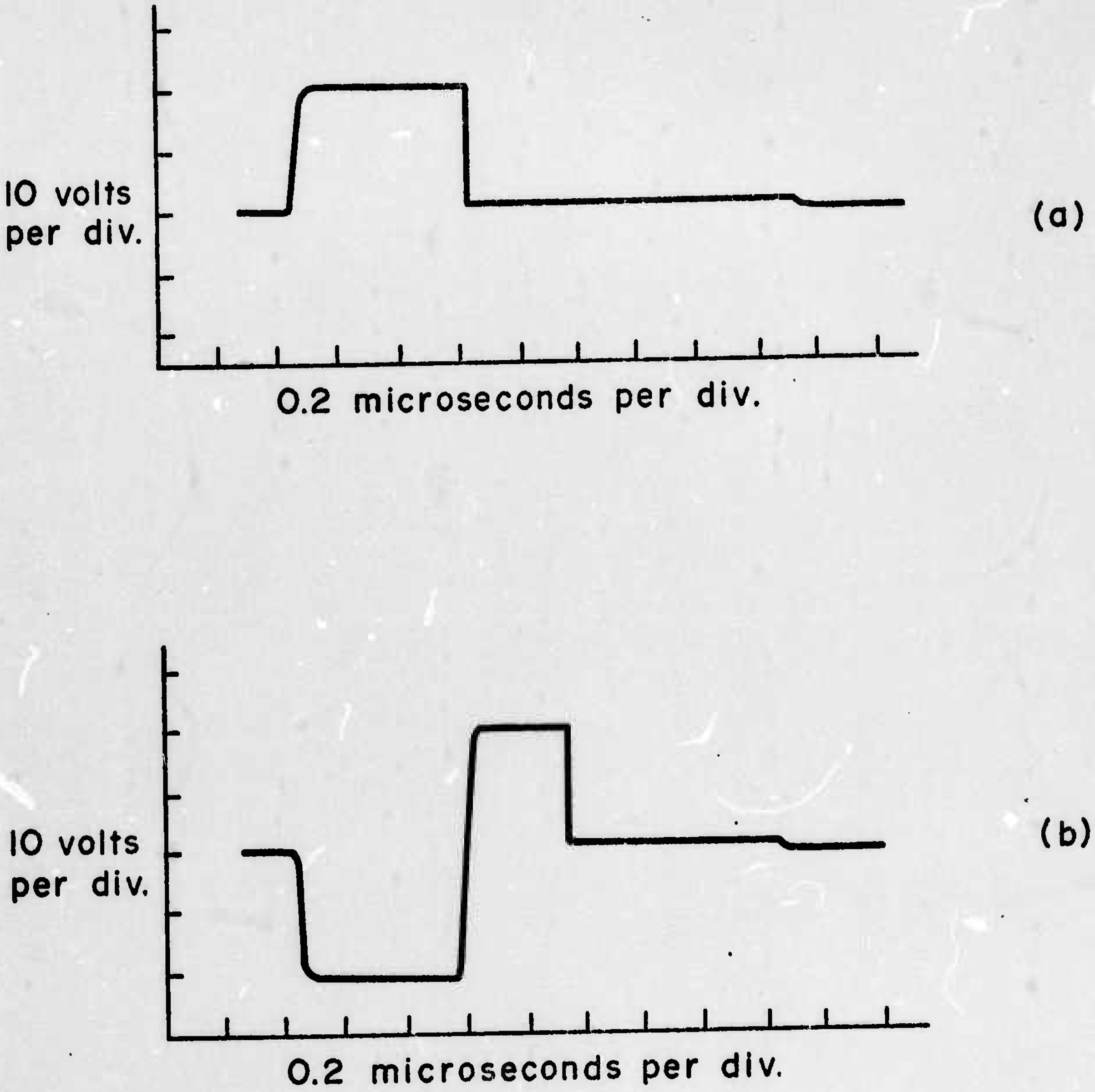
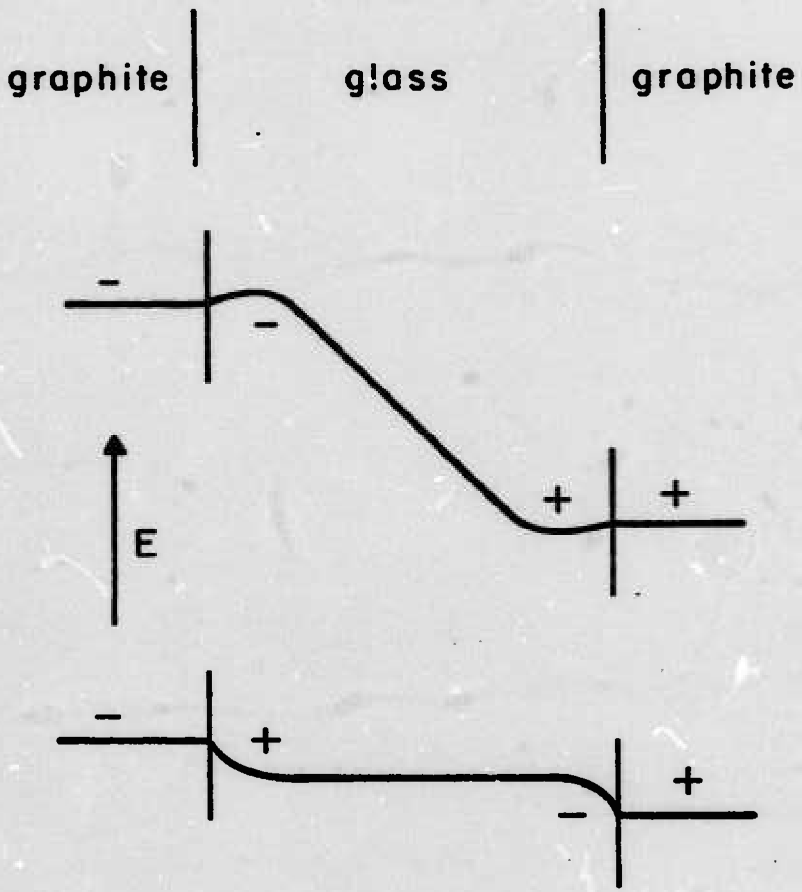
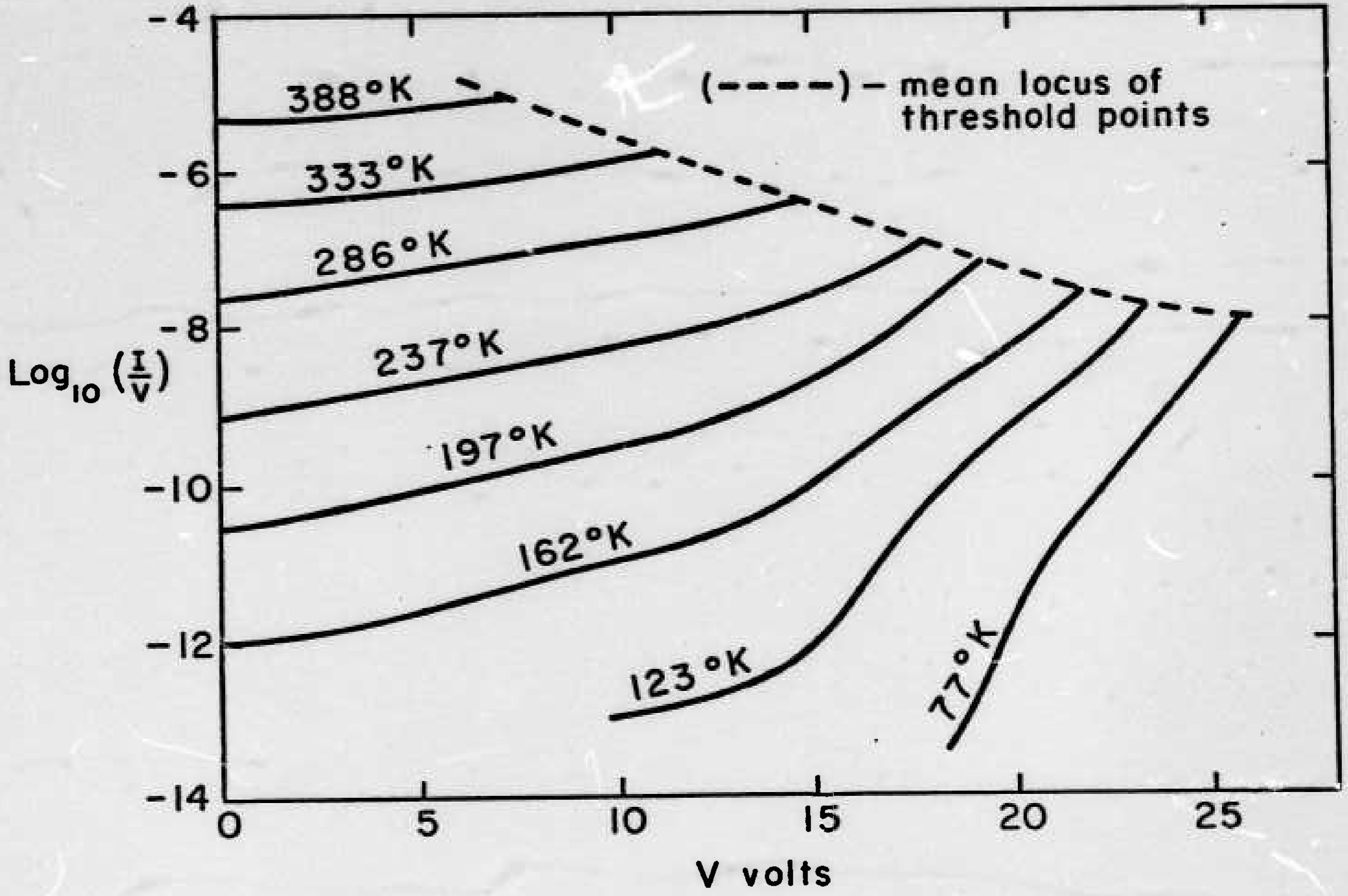

10 volts
per div.
0.2 microseconds per div.
(a)
10 volts
per div.
0.2 microseconds per div.
(b)

Fig. 1



electron energy profile in the OFF−state, as a result of carrier injection; maximum field in interior.

electron energy profile in the ON−state; most of voltage drop near contacts.


(-----) – mean locus of threshold points
388°K
333°K
286°K
237°K
197°K
162°K
123°K
77°K
$\mathrm{Log}_{10}\left(\frac{I}{V}\right)$
-4
-6
-8
-10
-12
-14
0
5
10
15
20
25
V volts

Fig