JOURNAL OF APPLIED PHYSICS VOLUME 39, NUMBER 6 MAY 1968

Stress State Required for Pyramidal Dislocation Movement in Zinc*

R. C. BLISH, II† AND T. VREELAND, JR.

W. M. Keck Laboratory of Engineering Materials, California Institute of Technology, Pasadena, California

(Received 21 December 1967)

A tension or compression stress in such a direction that basal slip is minimized can produce second-order pyramidal slip bands in zinc single crystals. The stress required to initiate pyramidal dislocation motion is not sensitive to temperature. However, dislocation velocity at a given stress is sensitive to temperature and the very small dislocation velocity at low temperatures has lead to an erroneous estimate of a "starting stress" for pyramidal dislocations. Dislocation velocity at a constant temperature was found to be a function of the magnitude, but not the sense of the resolved shear stress.

INTRODUCTION

There is a conflict in the literature with regard to certain properties of zinc deformed by pyramidal slip of the type $\{1\bar{2}12\}$ $\langle\bar{1}2\bar{1}3\rangle$. Bell and Cahn[1] showed that these pyramidal slip systems were responsible for the plastic deformation when basal slip is minimized. Gilman[2] performed the earliest experiments which were directed to a study of nonbasal plastic deformation. However, Gilman did not determine the active slip systems and reported a large difference in the nature of the plastic deformation when tension and compression loads were applied in the $\bar{a}$ direction. No difference in the plastic properties depending upon the sense of the stress state was found in subsequent work by Stofel and Wood[3] and Lavrent'yev and Salita.[4] Dislocation velocity measurements reported in this work furnish additional evidence that the characteristics of second-order pyramidal slip are independent of the sense of the stress state, under conditions wherein basal slip is minimized.

Lavrent'yev *et al.*[5] reported measurements of the "starting stress" for pyramidal slip in zinc as a function of temperature. Dislocation movement was measured in the present investigation at stresses well below their values of "starting stress," and a reason is suggested for the discrepancy between their measurement and ours.

EXPERIMENTAL

Specimens were prepared from crystals grown by the Bridgman technique. Acid machining was used exclusively to minimize the increase in dislocation density. The specimens were prismatic, usually about 1.5 cm long with a 1.5 cm×1 cm cross section. Two of the surfaces were parallel to $\{10\bar{1}0\}$ planes. The specimens were oriented for compression (or tension) along the $\bar{a}$ or the $\bar{c}$ direction of the single crystals. Stress pulses of controlled amplitude and duration produced by a rapid loading machine[6] were applied to the crystals, which were immersed in baths held at various temperatures. Low-modulus materials (Teflon or silicone rubber) were placed on each loading surface of the crystal to insure uniform application of the load. The $\{10\bar{1}0\}$ surfaces were chemically etch-pitted[7] before and after application of the stress pulses. Etch-pit densities, before application of the stress pulse ranged between 10^3 and 10^5 cm^{-2}. Etch-pit counts on the $\{10\bar{1}\,24\}$ surfaces,[8] indicated that the initial pyramidal dislocation density was always much less than the basal dislocation density.

RESULTS AND DISCUSSION

The slip bands formed under a constant stress were observed to grow at a constant rate, so average dislocation velocity was obtained by dividing the distance from the source of the slip band to its end by the duration of the stress pulse. The slip vector that received the largest resolved shear stress was parallel to the etched surfaces, so we presume that the observed velocity corresponds to the edge dislocation velocity.

Edge dislocation velocity as a function of stress was measured at room temperature for three different stress states. The stress state for the majority of the tests was $\bar{a}$-axis compression. Two tests were made under the condition of $\bar{a}$-axis tension and three tests utilized $\bar{c}$-axis compression. Figure 1 is a plot of edge dislocation velocity-vs-resolved shear stress on the active pyra-

* This work was used by R. C. Blish, II for partial fulfillment of Ph.D. requirements at the California Institute of Technology, Pasadena, Calif.

† Present address: Bell Telephone Laboratories, Inc., Murray Hill, N.J.

1 R. L. Bell and R. W. Cahn, Proc. Roy. Soc. (London), **A239**, 494 (1957).

2 J. J. Gilman, Trans. AIME J. Metals **206**, 1326 (1956).

3 E. J. Stofel and D. S. Wood, *Fracture of Solids* (Interscience Publishers, Inc., New York, 1963), p. 521.

4 F. F. Lavrent'yev and O. P. Salita, Sov. Phys.—Dokl. **8**, 803 (1964).

5 F. F. Lavrent'yev, O. P. Salita and V. I. Startsev, Sov. Phys. Metals Metallogr. (USA) **10**, 95 (1966).

6 T. L. Russell, D. S. Wood, and D. S. Clark, Acta Met. **9**, 1054 (1961).

7 R. C. Brandt, K. H. Adams, and T. Vreeland, Jr., J. Appl. Phys. **34**, 591 (1963).

8 K. H. Adams, R. C. Blish, II, and T. Vreeland, Jr., J. Appl. Phys. **37**, 4291 (1966).

9 K. H. Adams, R. C. Blish, II, and T. Vreeland, Jr., Mat. Sci. Eng. **2**, 201 (1967).

midal slip systems. No difference in the dislocation velocity-vs-stress for a compression or tension stress state is detected within experimental error. This is in agreement with the observations of Stofel and Wood and Lavrent'yev and Salita. Stofel and Wood obtained the same stress–strain curves for zinc subjected to $\bar{c}$-axis tension and compression at room temperature. Lavrent'yev and Salita observed the same amount of pyramidal dislocation motion on both the tension and compression sides of a beam subjected to pure bending. These observations indicate that the experimentally observed variation in starting stress from one crystal to another might be attributed to differences in crystal perfection. An additional example of the strong structure-sensitivity of the plastic properties of zinc is illustrated by the difference between the dislocation velocity measurements reported by Adams *et al.*[9] and those presented here. Adams *et al.* observed the same dislocation velocity at twice the stress (or a velocity 1000 times less for the same stress) in crystals with a higher initial etch-pit density of 10^5–10^6 cm^{-2}. The difference in crystal perfection was a consequence of different methods of producing test specimens of the desired shape from the large, randomly oriented single crystal (spark-erosion machining vs acid machining). A difference in the twinning behavior of crystals prepared by the two different methods has been discussed elsewhere.[10]

Figure 2 illustrates the effect of temperature upon dislocation velocity at 15 Mdyn/cm². The most striking feature of this data is that dislocation velocity does not increase monotonically with temperature. This phenomenon together with additional data on edge and screw dislocation velocity will be discussed in a subsequent paper.

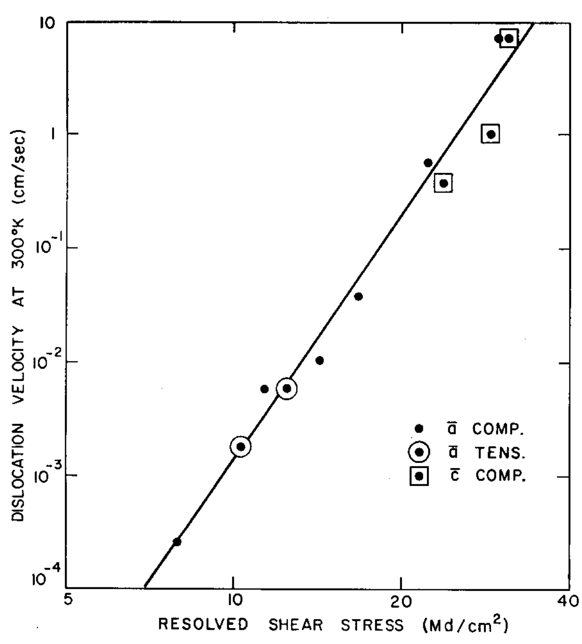

FIG. 1. Edge dislocation velocity as a function of resolved shear stress (Mdyn/cm²) on the active pyramidal slip systems at 300°K.

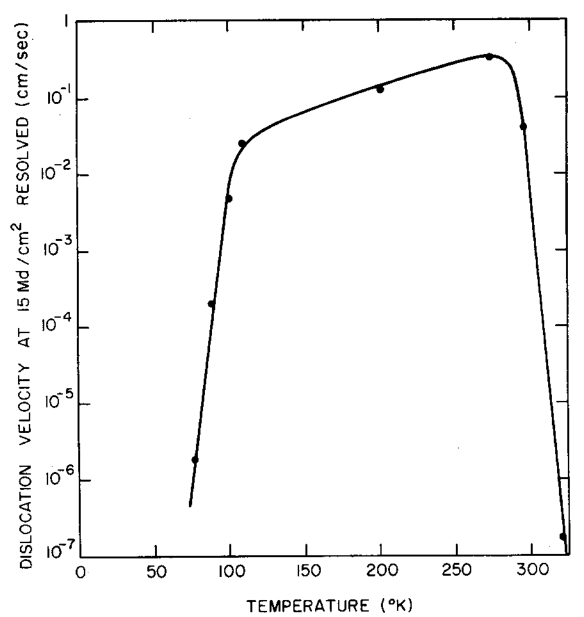

FIG. 2. Dislocation velocity at a resolved shear stress of 15 Mdyn/cm² as a function of absolute temperature.

Figure 2 also shows that dislocation motion occurs at stresses well below the "starting stress" reported by Lavrent'yev *et al.*, which was 10 Mdyn/cm² at 300°K rising increasingly rapidly to 130 Mdyn/cm² at 77°K. Dislocation motion was observed in the present work at 77°K at a stress of only $\frac{1}{10}$ of Lavrent'yev's "starting stress" reported for that temperature, whereas the observations are in agreement at 300°K. In fact, the "starting stress" observed in this investigation is about 10–20 Mdyn/cm² and is insensitive to temperature.

In order to understand this discrepancy one must consider how Lavrent'yev *et al.* measured the "starting stress." Dislocations in slip bands were observed to have moved from the outer fibers toward the neutral axis of a beam subjected to pure bending. The "starting stress" was taken as the elastic stress in the beam at the point where the dislocations in slip bands most closely approached the neutral axis. It was implicitly assumed that the dislocations had attained their equilibrium positions, where the stress could no longer move them. A serious error was made at the low temperatures where the dislocations require very long times to reach their equilibrium positions. Unfortunately, Lavrent'yev *et al.* did not report the magnitude of the bending moment, the duration of loading, or how close the dislocations

[10] R. C. Blish, II, and T. Vreeland, Jr., Phil. Mag. **17**, 849 (1968).

approached the neutral axis, so this hypothesis cannot be fully checked. It must be pointed out that the observations here do not constitute a new measurement of the "starting stress" (because this measurement depends upon the patience of the observer), but rather emphasizes a pitfall in the measurement of this property.

CONCLUSIONS

It is concluded that the sense of stress state has no effect upon the properties of plastic deformation on the second order pyramidal system in zinc. In this investigation dislocation velocity was found to be unaffected by a change from a compression to a tension stress state. The stress–strain curves obtained by Stofel and Wood[3] and the "starting stress" measurements of Lavrent'yev *et al.*[5] reveal no essential difference between the deformation behavior in tension and compression. These observations contradict those reported by Gilman.[2]

Dislocation velocity was measured in this investigation at stresses small in comparison with the "starting stress" reported by Lavrent'yev *et al.* The very small dislocation displacements detected by those investigators were not the equilibrium displacements and therefore their measurements did not give a true value of the "starting stress."

ACKNOWLEDGMENTS

The authors wish to express their appreciation to G. R. May for his tireless efforts in crystal preparation and to the U. S. Atomic Energy Commission who sponsored this investigation.

JOURNAL OF APPLIED PHYSICS VOLUME 39, NUMBER 6 MAY 1968

Transient Currents in Semi-Insulating CdTe Characteristic of Deep Traps*

K. R. Zanio, W. M. Akutagawa, and R. Kikuchi
Hughes Research Laboratories, Malibu, California
(Received 18 December 1967; in final form 22 January 1968)

The transport of charge in single crystals of semi-insulating cadmium telluride has been studied under the influence of deep trapping and subsequent thermal release of carriers from traps. Trapping and detrapping times for electrons and holes are determined directly from the shape of the transient response of surface-barrier devices to alpha particles. Hole-trapping times are 60 nsec; electron-trapping times range from 30 to 90 nsec. The measurement of the detrapping times from $-60°$ to $60°$ C indicates that an electron trap with an activation energy of 0.59 ± 0.04 eV can exist below the conduction band in semi-insulating material. The present measurement of drift mobilities, trap densities, and trapping cross sections does not require observation of a transit time. Furthermore, pulse analysis is not limited to times less than the transit time, a restriction in previous drift measurements. The theoretical response which accounts for both the trapping and detrapping of charge was derived by solving the kinetic differential equations which represent charge conservation. This extends the small-signal theory of transient currents in insulators to times beyond the transit time. Excellent agreement is found between experimental traces and theoretical shapes using a single-level trap model. Limiting cases which allow convenient measurement of the material parameters are described. In addition, the energy required to form an electron–hole pair is redetermined and found to be 4.9 ± 0.1 eV.

I. INTRODUCTION

By using drift techniques to study the transport of charge in semiconductors and insulators, their transport properties and trapping parameters can be measured. A new technique is presented here which allows direct measurement of these properties through an analysis of the transient response of surface-barrier devices to alpha particles. The present analysis using single crystals of semi-insulating cadmium telluride shows that the transport of injected charge is limited by deep traps. The interaction of charge with these traps permits a calculation of their density and depth below the conduction band.

The transient response of insulators in the small-signal mode has been analyzed on a simplified basis by Hecht[1] for the case where no detrapping occurs and for times less than the transit time.[2] This analysis has been valuable in determining mobilities and trapping times in a variety of high-resistivity materials. In more recent experiments,[3–6] emphasis has been on measuring the transit time of a thin sheet of charge which has spent a fraction of this time in traps. Since the velocity of the

* This work was supported by the U.S. Air Force Flight Dynamics Laboratory and the Atomic Energy Commission.

[1] K. Hecht, Z. Physik **77**, 235 (1932).
[2] In the present paper and in the Hecht analysis, the transit time is defined as the time required for injected charge to traverse the dimension of a device without suffering trapping events.
[3] W. E. Spear and J. Mort, Proc. Phys. Soc. (London) **81**, 130 (1963).
[4] J. G. Ruch and G. S. Kino, Appl. Phys. Letters **10**, 40 (1967).
[5] R. Raman, L. Azarraga, and S. P. McGlynn, J. Appl. Phys. **41**, 2516 (1964).
[6] A. R. Adams and W. E. Spear, J. Phys. Chem. Solids **25**, 1113 (1964).