A SIMPLE ANALYSIS OF THE PROPAGATING ACOUSTOELECTRIC HIGH-FIELD DOMAIN

Mosekilde, Erik

Published in:
Applied Physics Letters

Link to article, DOI:
10.1063/1.1651989

Publication date:
1968

Document Version
Publisher's PDF, also known as Version of record

experimental evidence for the validity of the above contention. Slip with Burgers vectors nonparallel to the surface is observed on two of the three {111} planes which are inclined to the (111) screw surface. Although the surface structure does not indicate the direction of slip on each system, the results are consistent with the assumption that these are the two unpredicted slip systems with highest resolved shear stress, and dislocation glide along these two systems to the interface relieves misfit strain in two directions. Dislocations on the predicted primary slip system in this geometry have no edge component parallel to the interface and consequently would not glide into the interface at the low yield stress shown in Fig. 1(*b*) for the composite crystal.

The plated edge surface, approximately a (210) surface, reveals a structure of apparent, yet unresolvable, fine slip on the primary slip plane, but does not distinguish whether the Burgers vector is primary or secondary. Two-dimensional relief of misfit strain at the interface is probably accommodated in this geometry by cross-slip of the glide-in dislocations; however, this is not resolved in the observed slip structure.

Although the shear modulus and critical yield stress for nickel are considerably larger in value than for copper, the elastic condition of the low-misfit interface formed by the thin nickel overgrowth on copper increases the ease with which dislocations are generated through the surface region of the crystal and, hence, decreases the yield strength during the initial stages of plastic flow. The model proposed above is not claimed to be applicable to all metal plating-substrate systems due to differences in the nature of the interface. A similar reduced yield strength observed in gold-plated copper composites in which the fraction of misfit is +13% is being investigated by the authors.

The authors gratefully acknowledge helpful discussions with Dr. W. A. Jesser and support by the Metallurgy Branch of the U.S. Office of Naval Research.

[1] E. S. Machlin, *Strengthening Mechanisms in Solids* (ASM, Ohio, 1960), p. 375.
[2] I. R. Kramer and L. J. Demer, *Progress in Materials Science* **9,** 133 (1961).
[3] A. R. C. Westwood, *Environment-Sensitive Mechanical Behavior* (Gordon and Breach, New York, 1966), p. 1.
[4] F. R. Lipsett and R. King, *Proc. Roy. Soc.* **B70,** 608 (1957).
[5] F. D. Rosi, *Acta Met.* **5,** 348 (1957).
[6] M. A. Adams, *Acta Met.* **6,** 327 (1958).
[7] I. G. Greenfield, L. C. DeJonghe, and W. R. Patterson, Technical Report No. 71, Dept of Mechanical and Aerospace Engineering, University of Delaware, Newark, Del. (1967).
[8] J. J. Gilman and T. A. Read, *Trans. AIME* **194,** 875 (1952); *J. Metals* **4,** 875 (1952).
[9] D. R. Brame and T. Evans, *Phil. Mag.* **3,** 971 (1958).
[10] T. Evans and D. R. Schwarzenberger, *Phil. Mag.* **4,** 889 (1959).
[11] W. A. Jesser and D. Kuhlmann-Welsdorf, *Phys. Stat. Sol.* **19,** 95 (1967).
[12] J. W. Matthews, *Phil. Mag.* **13,** 1207 (1966).
[13] J. W. Matthews and W. A. Jesser, *Acta Met.* **15,** 595 (1967).
[14] U. Gradmann, *Ann. Phys. (Lpz.)* **13,** 213 (1964); *ibid.* **17,** 91 (1965).
[15] E. R. Thompson and K. R. Lawless, *Appl. Phys. Letters* **9,** 138 (1966).

A SIMPLE ANALYSIS OF THE PROPAGATING ACOUSTOELECTRIC HIGH-FIELD DOMAIN

E. Mosekilde
Physics Laboratory III, Technical University of Denmark
Lyngby, Denmark
(Received 29 February 1968)

An analytical treatment of the uniformly propagating acoustoelectric high-field domain is presented in the limit of zero diffusion. Expressions for the electron density and the acoustic energy density as functions of the electric field are given. The domain velocity is determined.

Traveling high-field (HF) domains have been observed[1,2] in piezoelectric semiconductors when the free carrier drift velocity, v, exceeds the velocity of sound, v_s.

It has been suggested by Haydl et al.[3] and Autin[4] that the formation of an acoustoelectric HF domain takes place when the thermal flux has been amplified sufficiently to give rise to a negative differential conductivity. The domain is then supposed to be formed by the Ridley mechanism.

In this Letter we want to present a simple analysis of the steadily propagating acoustoelectric domain

similar in principle to the analysis of the stable Gunn domain given by Butcher et al.[5] We first state the general equations describing the amplification of acoustic flux by drifting carriers. We then impose the condition of stable propagation and obtain a set of equations which can be solved to give the free carrier density and the acoustic energy density as functions of the electric field, the carrier drift velocity, and the domain velocity itself.

The growth in space and time of the acoustic energy density, w, may be written as

$$\frac{\partial w}{\partial x} + v_s^{-1} \frac{\partial w}{\partial t} = \beta w - 2\alpha_L w \tag{1}$$

where it is assumed that the acoustic energy density is much greater than its thermal equilibrium value. Here α_L is the attenuation coefficient for nonelectronic losses taken to be independent of w, and β is the large-signal electronic amplification factor. In the Bray model[1] β depends on the carrier drift velocity, not the electric field, i.e.

$$\beta = B[(v/v_s) - 1]. \tag{2}$$

The acoustic buildup is limited to a frequency range $\Delta\omega \approx \omega_M$ around the optimum frequency $\omega_M = (\omega_C \omega_D)^{1/2}$, where ω_C and ω_D are the conductivity and diffusion frequencies as defined by White.[6] To simplify the discussion we treat β and α_L as independent of the acoustic frequency and equal to their respective values at ω_M. w is then to be understood as the density of acoustic energy in the range $\Delta\omega$.

The current density is given by the Weinreich relation

$$j = nev = ne\mu F - \mu\beta w \tag{3}$$

where F is the electric field, n the carrier density, e the carrier charge (taken to be positive), and μ the carrier mobility. We further need the law of charge conservation

$$\frac{\partial j}{\partial x} + e \frac{\partial n}{\partial t} = 0 \tag{4}$$

and Poisson's equation

$$\frac{\partial F}{\partial x} = \frac{e}{\epsilon}(n - n_0) \tag{5}$$

where ϵ is the static dielectric constant and n_0 the background density of negative ions.

To these equations we seek a solution representing a HF domain which propagates with a constant velocity, v_D, and without change in shape. The domain should be surrounded by neutral material in which $n = n_0$ and where the field and the acoustic energy density have constant values, F_R and w_R. For such a solution, the variables n, v, F, and w are functions of a single parameter $s = x - v_D t$.

The condition of stable propagation thus leads to the simplifications

$$\frac{\partial}{\partial x} = \frac{d}{ds} \quad \text{and} \quad \frac{\partial}{\partial t} = -v_D \frac{d}{ds}.$$

Moreover this condition determines the carrier drift velocity, v_R, in the neutral region. Here the electronic amplification and the nonelectronic losses must balance. This means that, as long as the domain is propagating, the current density in the sample is determined by

$$j_R = n_0 e v_R = n_0 e v_s (1 + 2\alpha_L/B) \tag{6}$$

independent of the sample voltage.

The charge conservation law (4) can now be integrated (the constant of integration being determined by the conditions in the neutral region):

$$v = v_D + (v_R - v_D) n_0/n. \tag{7}$$

Eliminating s from (1) and (5) we find

$$\frac{dw}{w} = \epsilon B g \frac{dF}{ne} \tag{8}$$

where

$$g = (v_R - v_D)/(v_D - v_s). \tag{9}$$

From experimental data on CdS and ZnO (ref. 7) the maximum rate of change of field on both the leading and trailing edges of the domain can be estimated as $3 \cdot 10^6$ V/cm^2 corresponding to a maximum degree of charge accumulation or depletion of 0.2%. We thus see that in contrast to the Gunn domain the acoustoelectric HF domain is accompanied by a weak modulation of the free carrier density. Replacing n in the denominator of (8) by n_0 and integrating we obtain for the acoustic energy density

$$w \cong w_R \exp\left\{\frac{\epsilon B g}{n_0 e}(F - F_R)\right\} \tag{10}$$

(the approximation $n \cong n_0$ is equivalent to neglecting a minor difference in w_R between the two parts of the neutral region).

Substituting for w and v in (3) gives

$$ne\,[v_D + (v_R - v_D) n_0/n] = ne\mu F - \frac{\mu B w_R}{v_s} \times \left[v_D - v_s + (v_R - v_D) n_0/n\right] \exp\left\{\frac{\epsilon B g}{n_0 e}(F - F_R)\right\} \tag{11}$$

from which n is determined as a double valued func-

tion of the electric field corresponding to a depletion layer in the leading edge of the domain and an accumulation layer in the trailing edge.

If finally we impose the condition $n = n_0$ for $F = F_D$ on (11), F_D being the maximum field of the domain, we obtain

$$g = \frac{n_0 e}{\epsilon B(F_D - F_R)} \ln\left\{\frac{n_0 e(F_D - F_R)}{2\alpha_L w_R}\right\} \equiv C/B, \quad (12)$$

(9) can then be solved to give the domain velocity

$$v_D \doteq v_s(1 + 2\alpha_L/(B + C)). \quad (13)$$

The above model results in a domain velocity that is a few tenths of a percent greater than the velocity of sound. This is due to a net flux amplification at the leading edge of the domain and a net attenuation at the trailing edge. Moreover, the model gives a domain velocity that increases slightly with the biasing voltage of the sample, whereas a theory based on a negative differential conductivity is supposed to give a decrease in v_D when the drive is increased. Some experimental results[1] seem to indicate a slight reduction in the oscillation period when the sample voltage is raised.

We should like to stress that some of the fundamental assumptions of our model are still under discussion. This relates, for example, to the modification of the electronic amplification factor necessary under nonlinear conditions and the importance of nonlinear acoustic losses. We must conclude however that the stable propagating acoustoelectric HF domain is compatible with the Bray model.

I have benefited strongly from discussions with Prof. N. I. Meyer. I am grateful to M. H. Jørgensen for valuable suggestions and to M. Bruun who made his data on domain formation available to me prior to publication.

[1] R. Bray, C. S. Kumar, J. B. Ross, and P. O. Sliva, *J. Phys. Soc. Japan (Suppl.)* **21**, 483 (1966).
[2] W. H. Haydl and C. F. Quate, *Phys. Letters* **20**, 463 (1966).
[3] W. H. Haydl, K. Harker, and C. F. Quate, *J. Appl. Phys.* **38**, 4295 (1967).
[4] B. Autin, *Phys. Stat. Sol.* **24**, 501 (1967).
[5] P. N. Butcher, W. Fawcett, and C. Hilsum, *Brit. J. Appl. Phys.* **17**, 841 (1966).
[6] D. L. White, *J. Appl. Phys.* **33**, 2547 (1962).
[7] M. Bruun and N. I. Meyer, unpublished.

OBSERVATION OF PICOSECOND PULSES FROM A Nd:YAG LASER

M. Bass and D. Woodward
Raytheon Research Division
Waltham, Massachusetts
(Received 4 March 1968)

Ultrashort pulses are observed in the output of a Pockel's cell Q-switched, pulsed Nd:YAG laser. This result suggests that self-locking effects occur in Nd:YAG lasers and that the output of such lasers may, in general, be composed of many picosecond pulses.

Recently Giordmaine et al.[1] developed the two-photon absorption-fluorescence technique for the observation of ultrashort (picosecond) pulses from a bleachable dye Q-switched, pulsed Nd:glass laser. Since then, this technique has been used to show that there are picosecond pulses in the output of pulsed Nd:glass and ruby lasers.[2] The experiment described below shows that picosecond pulses are also present in the output of a Pockel's cell Q-switched, pulsed Nd:YAG laser.

The experimental setup is sketched in Fig. 1. The laser configuration was chosen for optimum energy per pulse (~100 mJ) and short pulse duration (~40 nsec). All intracavity surfaces were antireflection coated to have less than 0.2% reflectivity at 1.06 μ. A 10^{-3} M solution of rhodamine B in dichloroethane ($n_{1.06\mu} = 1.445$) was used as the two-photon absorbing-fluorescing liquid. This choice was made because rhodamine B in dichloroethane has very little attenuation at 1.06 μ

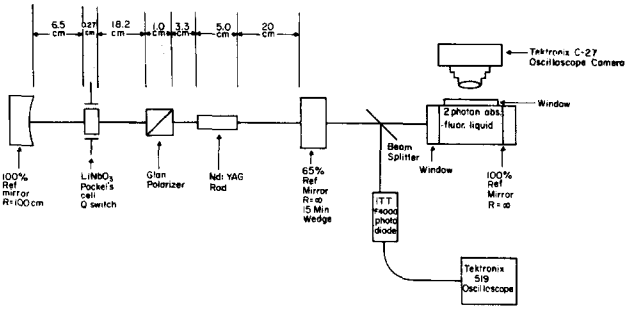

Fig. 1. Experimental apparatus.