Physica 143B (1986) 152-154
North-Holland, Amsterdam

A PHASE-SLIP MODEL OF SWITCHING*

R. P. HALL†, M. F. HUNDLEY, and A. ZETTL§

Physics Department, University of California, Berkeley, CA 94720, U.S.A.

We review recent experiments which suggest that charge-density wave (CDW) amplitude fluctuations play a critical role in switching, and present a model of switching based on amplitude collapse at phase-slip[1] centers.

1. INTRODUCTION

In most crystals of charge-density wave (CDW) conductors, the onset of CDW motion is gradual. Past a threshold electric field E_T, a typical IV curve smoothly becomes nonlinear while the corresponding derivative curve dV/DI remains continuous.[2] In some crystals, however, CDW motion is such an abrupt function of the applied field that an actual (hysteretic) jump or "switch" appears in the IV characteristic.[3] A switching IV curve is shown in the top trace of Fig. 1b.

Below threshold, ac conductivity measurements show that switching CDWs are *overdamped* and dynamically equivalent to nonswitching CDWs.[4] Only at, and above, threshold do switching CDWs behave dramatically differently from non-switching CDWs. The threshold fields of crystals in the switching regime are large and *temperature-independent*, implying a novel mechanism of CDW depinning.[5] Switching CDWs make an *immediate* transition from the pinned static state to the high-field, high-conductivity sliding state.[5] Switching CDWs may respond *chaotically* to combined dc and ac fields,[6] and the low frequency ac conductivity of sliding CDWs is *inductive* in the switching regime.[4]

Recently we have found that CDW amplitude fluctuations may explain the unique properties of switching crystals.[7] We will review the experimental evidence for amplitude fluctuations in $NbSe_3$ and Fe_xNbSe_3 and then present our model of switching.

2. EXPERIMENTAL

Our experiments employ a four-terminal probe with which we can non-perturbatively measure dc conductivity in different regions of a sample. Fig. 1a shows schematically the probe arrangement. Current leads, terminals 1 and 4, are attached to the ends of a crystal. Two additional non-invasive voltage-sensing probes, terminals 2 and 3, can be independently translated along the length of the crystal.

Figure 1b shows IV characteristics of a sample of Fe_xNbSe_3. The top trace represents the IV curve of the "whole" crystal, measured between terminals 1 and 4. Two switches, S1 and S2, are clearly observed at bias currents I_{S1} = 130 μA and I_{S2} = 160 μA. The three lower displaced traces in Fig. 1b represent the IV characteristics of different segments of the crystal, with the voltage probes at the positions indicated in Fig. 1a. At the onset I_{S1} of nonlinear conduction for the entire sample, uniform CDW current is *not* observed throughout the sample. By repositioning probes 2 and 3, we have deter-

*Research supported by NSF grants DMR 83-51678 and DMR 84-00041.
†IBM Predoctoral Fellow.
§Alfred P. Sloan Foundation Fellow and NSF Presidential Young Investigator.

0378-4363/86/$03.50 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division)
and Yamada Science Foundation

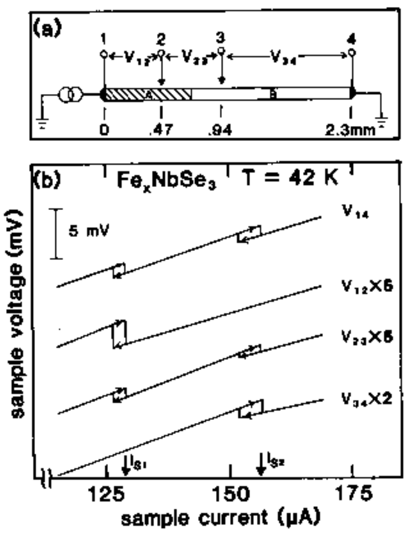

FIGURE 1
(a) Schematic of four-terminal probe. (b) IV characteristics of a switching crystal, measured over entire crystal and successive sections.

mined that the crystal used for Fig. 1 contains two independent regions, identified as "A" and "B" in Fig. 1a. The common boundary of regions A and B is 776 ± 20 μm from terminal 1. An upper bound for the full width of their interface, which we identify as a phase-slip center, is approximately 25 ± 20 μm. Simultaneous measurements of the narrow band noise spectrum demonstrate that the phase-slip center remains intact even after *both* regions A and B depin. Cleaving experiments suggest that in switching crystals phase-slip centers may coincide with localized strong pinning sites.[7]

3. A SIMPLE MODEL OF SWITCHING

We suggest that switching may be explained by strong pinning, phase polarization, and amplitude collapse. We postulate that switching crystals consist of two types of regions: weakly pinning bulk regions and strongly pinning phase-slip zones. When an applied electric field exceeds the bulk threshold, the field polarizes a CDW about its strongly pinned segments. Further increase of the applied field does not dislodge the phase of a strongly pinned CDW segment; instead, the elastic energy cost of further phase polarization drives the CDW amplitude to zero. The magnitude of the force required to prevent phase advancement during amplitude collapse defines the criterion for "strong pinning".

When amplitude collapse occurs, the CDW phase at a strong pinning center changes by *exactly* π and is then at its most energetically unfavorable value. The strong pinning potential and applied electric field quickly advance the phase by an additional factor of π, whereupon the CDW repins. In essence, the phase hops by 2π. (Ginzburg-Landau type equations for the CDW order parameter, such as Gorkov's[1], will in general prevent multiple 2π hops.) The hop duration scales as the ratio of the weak to strong pinning potentials, and so may be instantaneous on the time scale of bulk phase motion. After a phase hop, phase polarization is reduced and the amplitude recovers from zero, setting the stage for the next cycle of phase pile-up and amplitude collapse.

Depending on the degree that phase polarization is relieved, amplitude recovery may be incomplete before the next collapse. Pinning and coupling forces will depend on the CDW amplitude, so the effective pinning potential may actually be *reduced* as the CDW begins to slide. At some critical value of amplitude stiffness, positive feedback causes an immediate transition or "switch" to the high-field, high-conductivity state at the threshold field E_T.

We have constructed a discrete model of switching based upon these ideas. For simplicity, the bulk phase ϕ_{BULK} is treated as a rigid classical entity. ϕ_{BULK} couples to a normalized electric field e, an impurity potential $\sin\phi_{BULK}$, and a strongly pinned phase ϕ_{PSC}. ϕ_{PSC} changes by hops of 2π when the CDW amplitude Δ at the

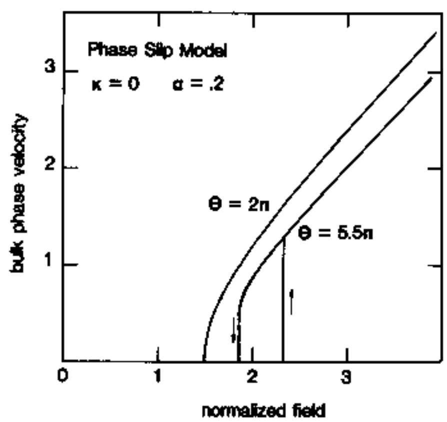

FIGURE 2
Nonswitching and switching IV characteristics of the phase-slip model.

strong pinning site collapses, and Δ obeys simple relaxational dynamics driven by the square of the phase polarization, $(\phi_{BULK} - \phi_{PSC})^2$:

(1) $\dot{\phi}_{BULK} = e - \sin\phi_{BULK} - \alpha\Delta(\phi_{BULK} - \phi_{PSC})$

(2) $\phi_{PSC} \rightarrow \begin{cases} \phi_{PSC} & \text{if } \Delta \neq 0 \\ \phi_{PSC} + 2\pi\,\mathrm{sign}(\phi_{BULK} - \phi_{PSC}) & \text{if } \Delta = 0 \end{cases}$

(3) $\kappa\dot{\Delta} = -(\Delta + [\phi_{BULK} - \phi_{PSC}]^2/\theta^2 - 1)$

In (1), phase-phase coupling must disappear when Δ collapses, and this is accomplished by making the coupling proportional to Δ. Switching is caused by this intrinsic nonlinearity, but is insensitive to exactly how the nonlinearity is incorporated; the important physics is "no amplitude, no coupling."

Parameters in this model are α, the stiffness of the phase mode; κ, the ratio of phase to amplitude relaxation rates; and θ, the stiffness of the amplitude mode. θ determines whether switching occurs, and for $\kappa = 0$, switching occurs exactly for $\theta > 2\pi/(1 - 1/\sqrt{3})$. Figure 2 shows switching and non-switching IV curves for $\kappa = 0$ and $\alpha = .2$, with $\theta = 5.5\pi$ and $\theta = 2\pi$, respectively.

4. CONCLUSION

Our phase-slip model qualitatively reproduces many of the experimental characteristics of switching.[8] Two features are integral to our description of switching. First, amplitude collapse is caused by phase polarization at phase-slip centers. Second, amplitude supression feeds back into amplitude-dependent pinning terms to trigger a switch to a high-field state.

ACKNOWLEDGEMENTS

We wish to thank Professor Leo Falicov, Professor S. Doniach and M. Inui for useful discussions.

REFERENCES

1. Phase-slips at current-injection contacts have previously been discussed. See N. P. Ong *et al.*, Phys. Rev. Lett. 52 (1984), 663 and L. P. Gorkov, JETP Lett. 38 (1983), 87.

2. For a review, see G. Grüner and A. Zettl, Phys. Reports 119 (1985), 117.

3. A. Zettl and G. Grüner, Phys. Rev. B26 (1982), 2298.

4. R. P. Hall and A. Zettl, Solid State Comm. 55 (1985), 307.

5. R. P. Hall and A. Zettl, Solid State Comm. 50 (1984), 813.

6. R. P. Hall, M. Sherwin, and A. Zettl, Phys. Rev. B29 (1984), 7076.

7. R. P. Hall, M. F. Hundley, and A. Zettl, Phys. Rev. Lett., in print, and to be published.

8. M. Inui, S. Doniach, R. P. Hall, and A. Zettl, to be published.