

## Interest Grows in Semiconductor Instabilities

The physics of semiconductors is now so diffuse that nearly all major conferences on the subject are becoming large, formal and unproductive, with parallel sessions carefully arranged to frustrate those who dare to dabble in two branches of the field. A tendency is now developing towards the specialized meeting, maximizing the number of participants and minimizing the dilution with observers. This tendency was well exemplified by the recent conference on Instabilities in Semiconductors held at the Thomas J. Watson Research Center of IBM at Yorktown Heights, N. Y., on 20, 21 March. About 200 scientists attended; this number indicates the remarkable growth of interest in a field that hardly existed five years ago. Then Ohm's law was maintained with the same rigor as a Papal Encyclical, and he who observed a wavering ammeter threw away his sample. Today it is normal to be unstable.

The program concentrated on three types of instability: acoustoelectric effects, negative differential mobilities and microwave emission in indium antimonide. There was also a miscellaneous selection of papers on other topics, and among these particular interest was aroused by two papers on amorphous switching devices. A. David Pearson (Bell Telephone Laboratories), who in 1962 first reported switching effects in arsenic-tellurium-iodine glasses, reviewed the work done since that time and concluded that in many glass systems the effect was the result of local melting followed by a vitreous-crystalline phase transition. His argument was reinforced with a movie that clearly displayed liquid formation, with tiny particles of dirt slopping about on the molten pools. (Three frames are reproduced in the figure on this page.)

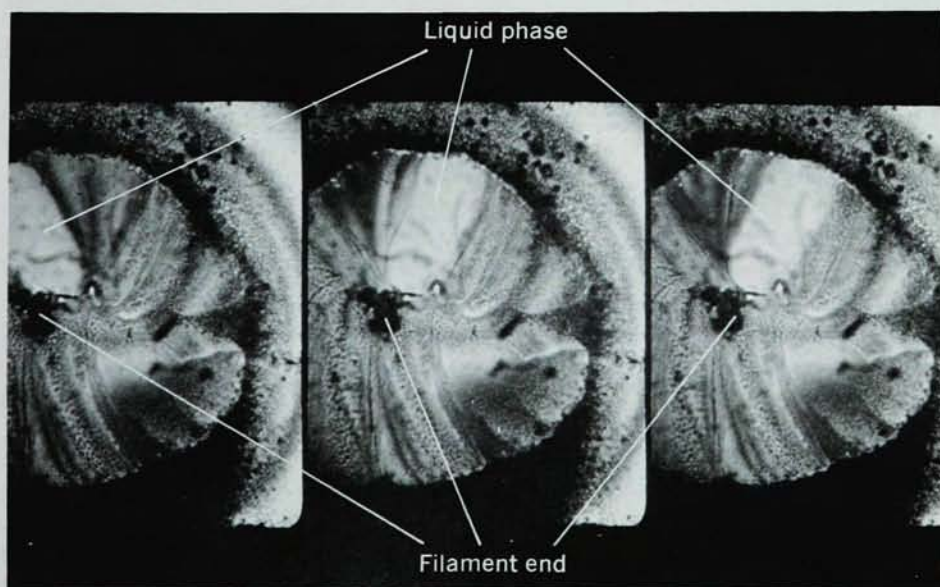
Helmut Fritzsche (University of Chicago) remained unconvinced. His ideas about switching were more complex and involved a detailed theory of conduction in amorphous solids. However, he started by proving that in the devices made by Stanford Ovshinsky at Energy Conversion Devices—Fritzsche, as a consultant to

ECD, is in close touch with their results—the energy available during switching was not sufficient to raise a significant volume to the melting point of the glass. The glasses used could be considered as semiconductors, with both conduction and valence bands distorted so severely that they overlapped near the middle of what was once the forbidden gap. The mobility of these states within the forbidden gap is very low, but the conduction and valence-band states show a more normal mobility. As a result the mobility shows an activation energy, and this almost completely determines the change of resistivity with temperature, because the density of carriers is almost temperature independent. It would be very easy to make an ohmic contact to such a semiconductor, for there is a large density of states near the Fermi level. Fritzsche showed that the overlapping states provided a high concentration of hole and electron traps, and a nonequilibrium carrier distribution could be frozen in. He argued that his model explained not only the switching phenomena, but also other electrical and optical effects.

Fritzsche's novel theory aroused

much interest, and he faced a barrage of mainly hostile questions. After ten minutes the chairman closed the discussion with the situation unresolved, and many questioners still clamored for attention.

**Acoustoelectric effects.** Instabilities resulting from acoustoelectric effects are fairly new phenomena, and a series of papers showed that these effects are now understood in general. A rigorous theory of domain formation and stabilization is, however, still lacking. There is a growing tendency to move away from bulk acoustoelectric effects towards surface waves, and this school was well represented by a group from Stanford University—Gordon S. Kino, Tom M. Reeder and Kenneth M. Lakin. They had experimented with an interacting system of silicon and lithium niobate, with the carriers drifting in the silicon epitaxial layer strongly affected by the acoustic wave propagated in the lithium-niobate crystal. The two media were separated by about 50 mm. The interaction covered a wide band of frequencies from 20 MHz to 1.2 GHz, with a peak electronic gain as high as 60 db/cm. Because the transducer loss can be held quite low the system



**LIQUID-PHASE PATCH** of semiconducting glass alloyed with lead moves about on the surface of this lead-glass-gold sandwich, but is always attached to the conducting glass "filament." These three adjacent movie frames were shot at 16 frames/sec. (From A. David Pearson and C.E. Miller, *Appl. Phys. Lett.* 14, 280, 1969.)

offers considerable potential in devices.

Another interesting paper in this session, this time on bulk effects, was by Stanley Zemon and Joseph Zucker (General Telephone and Electronics). They had set out to explain the fall in frequency of maximal acoustic intensity that is observed for a high-flux domain in a piezoelectric semiconductor such as cadmium sulfide. They showed that the effects were caused by parametric amplification, with subharmonics growing at the expense of the pump signal.

**Negative differential mobility.** Instability arising from negative differential mobility still attracts much interest, although much of the controversy surrounding the topic has departed. It is now generally agreed that the Gunn effect is the result of the formation of a traveling high-field domain consequent on electron transfer from light-mass to heavy-mass conduction-band states. With this agreement has come a reaction, and enthusiasts are seeing transferred-electron effects in all kinds of unlikely situations. George Persky and Dirk J. Bartelink (Bell Telephone Laboratories) suggested that breakdown in indium antimonide is not a simple avalanche process, but is initiated by electron transfer within the central conduction-band minimum. This band is extremely nonparabolic, and the higher-energy states are much heavier than the low-energy states. Persky and Bartelink had calculated that the transfer would give a negative differential resistance, so leading to an instability and a magnification of the field within the sample. They argued that their theory explained why indium antimonide broke down at such low electric fields.

The discussion revealed a piquant situation. The delegation from the Royal Radar Establishment, the original proponents of electron transfer in gallium arsenide, strongly resisted this new candidate. They claimed that calculations for indium arsenide, a similar material to indium antimonide with a markedly nonparabolic conduction band, showed no hint of a negative differential mobility. This controversy also remained unresolved, but it drew attention to a new and powerful technique that is now available for calculations of high-field effects in semiconductors. Until last year the

only methods known for deducing the field dependence of carrier velocity relied on a variety of approximations. As the calculation was an important one, providing the basis on which the Gunn effect and other microwave instabilities in gallium arsenide were to be explained, there was some bickering among the theorists as to whose approximations were least objectionable.

The argument was settled when two computing techniques were developed for solving the problem without any approximations. The first method was a Monte Carlo calculation and the second involved an iterative solution of the Boltzmann equation. Few details of these calculations have yet been published, and the audience was particularly interested to hear a paper on the subject by David Rees (Royal Radar Establishment) who played a major part in inventing the new techniques. Rees dealt with the iterative solution and showed how it could give the time response of the electron population to a voltage impulse. He deduced the frequency response of a gallium-arsenide oscillator working in the regime of limited space-charge accumulation, and he concluded that there was little prospect of making such oscillators work at frequencies beyond 80 GHz. The silence with which this result was greeted made one suspect that the audience abounded with engineers planning submillimeter wave-communication systems.

The second day of the conference opened with a review by Jack Smith Jr (IBM) of experiments on negative resistance effects in germanium. IBM were the first to discover that germanium showed an instability at high fields, and have since extended their experiments to display a wealth of interesting effects. E. G. S. (Ted) Paige (Royal Radar Establishment) tried to explain these effects on the basis of electron transfer between the various minima of a very complicated conduction band. He had used the Monte Carlo method for his calculations and concluded, with some reservations, that the observed effects were not inconsistent with his theory. Following their successful experiments with germanium, the IBM team had looked around for more material that might show negative resistance resulting from electron transfer and, in two papers, reported their success.

**Electron transfer.** The first series

of experiments was on indium antimonide, and James C. McGroddy, Marshall I. Nathan and John E. Smith Jr (IBM), together with William Paul and Sylwester Porowski (Harvard University) had shown that at 77 K and atmospheric pressure n-type indium antimonide demonstrated avalanche breakdown at fields above 200 volt/cm. With increasing hydrostatic pressure the energy gap between the valence band and the light-mass conduction-band minimum increases, while the heavy-mass subsidiary conduction-band minima approach closer to the light-mass states. Eventually there is a transition from avalanching to electron transfer. The experiment can be used to give a number of the important parameters for indium antimonide.

In the following paper Max Lorenz, McGroddy and Tom S. Plaskett (IBM), with Porowski, explained how similar effects could be obtained by alloying indium antimonide with gallium antimonide. An appropriate mixed crystal showed the Gunn effect at room temperature, with threshold fields as low as 600 volt/cm. This group thought that this material might have practical importance, because the negative resistance was at least as large as in gallium arsenide. The audience showed some scepticism about the possibilities of making devices from a semiconductor with such a low thermal conductivity, but the paper clearly opened minds to the potentialities of mixed crystals in this field.

The prototype transferred electron material, gallium arsenide, has now been studied so thoroughly that it almost escapes mention at research conferences of this type. However, Melvin P. Shaw, Peter R. Solomon and Harold L. Grubin (United Aircraft Laboratories) had been so incensed by the variability of their results on the gallium arsenide with which they had been supplied that they had codified the types of electrical behavior they observed and developed a theory to account for the effects. They pointed out that the ideal velocity-field relationship could rarely explain the electrical properties of gallium-arsenide samples completely. Conditions at the contacts, and in particular at the cathode, could cause instabilities that were distinct from the Gunn effect. Their theory could explain most of the results that had been observed at their own and other laboratories. Some members of the audience questioned

the advisability of working with bulk single crystals of gallium arsenide, which are known to be inhomogeneous, but Shaw, Solomon and Grubin maintained they had seen similar results on epitaxial gallium arsenide.

A number of papers had been presented on microwave generation in indium antimonide, and the conference closed with a panel session on this topic. The panel consisted of Betsy

Ancker-Johnson, Bartelink, George Bekefi, David K. Ferry, Kino and Charles W. Turner, with Maurice Glicksman as chairman. A variety of views were given on the probable mechanism of the observed effects, ranging from acoustic-wave amplification to two-stream instabilities, and from surface effects to plasma breakdown. There certainly are many ways in which semiconductors can become

unstable, and indium antimonide is one material in which most of these effects can occur and probably do. And on this note the conference ended.

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## Progress in Thin-Film Studies Discussed in Boston

The theme of the recent conference on thin films, and the main emphasis of the invited and contributed papers, was the structure-sensitive properties of films. More than one third of the 110 papers were addressed to problems of film formation or to structural and metallurgical properties.

This International Conference on Thin Films, convened in Boston on 28 April, was the fourth of a series that started in 1959 with the meeting called by C. A. Neugebauer (General Electric Research Center) at Bolton's Landing, N.Y. Subsequent conferences held in 1961 at Louvain, Belgium and in 1965 at Clausthal-Göttingen continued to provide an international forum and an opportunity for reassessment of progress made towards a better understanding of the scientific and technological aspects of thin films.

The high level of interest in mechanisms of nucleation and epitaxial growth that characterized the earlier conferences was still in evidence at this one. However, the usual skirmishes between the proponents of atomistic and capillarity models did not develop. Speakers tended, instead, to concentrate on critical tests of key relationships in the atomistic theory.

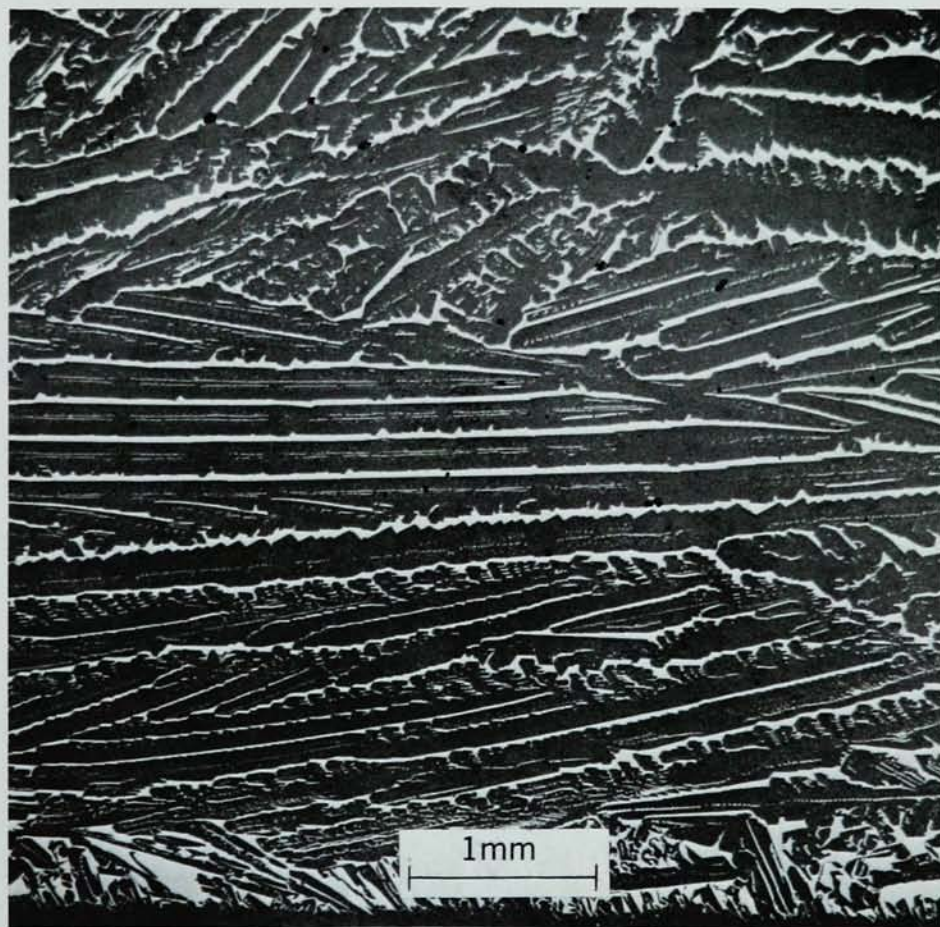
**Atomistic Model.** David Campbell (Plessey) reviewed some of the more controversial aspects of the atomistic model. Examples of these aspects are the relationships between saturation density of nuclei  $N_s$  and substrate temperature  $T$  for initially complete and incomplete condensation, the derivation of values for adsorption energy  $E_a$  and diffusion energy  $E_d$  and the roles of nucleation and island coalescence in epitaxial growth.

Hans Bethge (Deutsche Akademie der Wissenschaften) discussed the nature of nucleation sites in some detail and considered some of the factors influencing epitaxial growth. He dem-

onstrated that the density of intrinsic defect sites on the face of an alkali-halide crystal is sufficiently high for one to assume always that it is higher than the number of nuclei formed. The number of such sites activated, and the size of the clusters formed, depends upon the deposition rates. He also speculated on the role of electrical double layers in enhancing epitaxial orientation and pointed out that an array of charged surface vacancies, generated for example by electron bombardment, could give rise to surface fields at the substrate with mag-

nitudes of the order of  $10^3$ – $10^4$  volts/cm.

The nature of such electron-induced surface vacancies, for example in potassium chloride substrates, was considered by Thor Rhodin (Cornell University) who showed that they were chlorine vacancies that could be stabilized by nucleating thin layers of silver or gold. Subsequent deposition of the same metal on such nucleated surfaces at higher temperatures promoted epitaxial growth, whereas deposition on untreated surfaces did not. Rhodin argued that bombardment-induced



**TWO-PHASE FILM** grown by electron-beam microzone crystallization on a glass substrate. Photograph shows an ordered array of indium filaments contained in a matrix of single-crystal indium antimonide dendrites; thickness of the film is about 5 microns. (From N. Davis and A. Clawson, to be published in *J. Vac. Sci. Technol.*)