

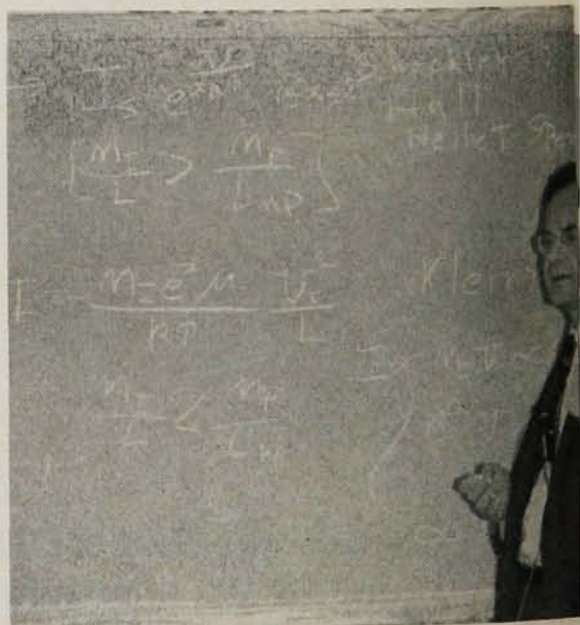
SPACE CHARGE EFFECTS in DIELECTRICS

*A Conference Report by George H. Heilmeyer
and Peter J. Warter, Jr.*

A CONFERENCE to discuss space-charge effects in dielectrics was held in Westhampton Beach, N. Y., on June 13, 14, and 15, 1962. Such a conference was originally proposed by Marvin Silver of the Office of Army Research (Durham) and Abraham Many of the Hebrew University in Jerusalem. A committee consisting of Many, Silver, David Fox, Albert Rose, Fritz Stöckmann, and George Warfield was formed to help in selecting the papers and planning the details of the meeting.

Financial support for the meeting was obtained through the United States Office of Naval Research, and the host institution was the State University of New York, Long Island Center. Because the facilities of the new Long Island Center had not been completed, the conference was held at the Bath and Tennis Club, an attractive hotel in the nearby resort town of Westhampton Beach. The selection was an ideal one, and the facilities of the hotel were extremely well suited to an informal meeting. Since the meeting was held in midweek before the normal resort season, the conferees had the hotel to themselves. For the same reason, these facilities, so conducive to a suc-

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Albert Rose—double-injection currents.

cessful informal meeting, could be obtained for rates comparing favorably with commercial hotel accommodations in a typical large city.

Fifty-six conferees, including eight from four foreign countries (England, Germany, Switzerland, and Israel), were registered. In addition, several brought their families, bringing the total attendance to approximately seventy people.

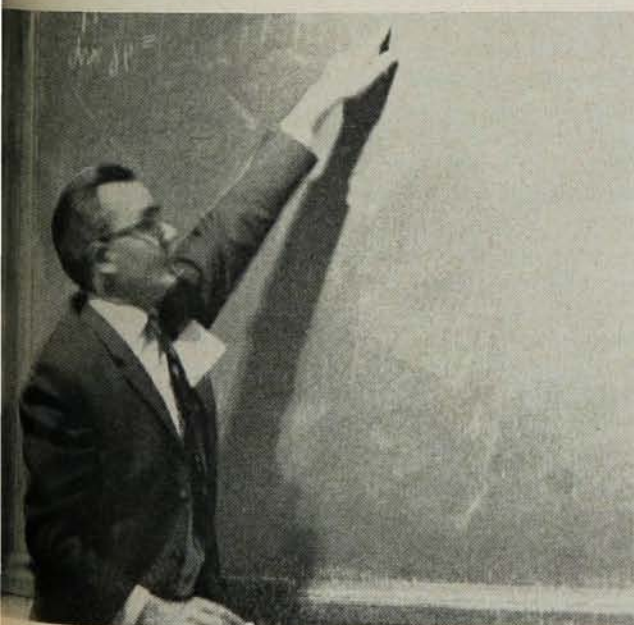
The opening event on Tuesday evening was an informal get-together of the conferees in the Club's cocktail lounge, for which the hotel management had thoughtfully provided beer and pretzels. The usual cocktail party and banquet were held on Thursday evening. The banquet had no program and no speaker, and it would seem that there is much to recommend this format.

The committee had originally planned to hold an evening session rather than an afternoon session in order to allow those attending to make full use of the excellent ocean or pool bathing and tennis facilities of the Club. The only uncooperative factor was the weather, which for three days oscillated between a dull dreary mist and heavy rain, causing two postponements of the period allotted for extracurricular activities. As a result, the first day was tightly packed with three full technical sessions.

The program consisted of twenty-two papers divided among five sessions. Each speaker was allotted twenty-five minutes, and another fifteen minutes was scheduled for the discussion of each paper. This permitted a free exchange of ideas and extensive discussion. In addition, the informal atmosphere of the conference further promoted an exchange of information.

AFTER some introductory remarks by Prof. Fox, Henry Sommers called the first session to order with a paper on transient space-charge-limited currents in molecular crystals by Abraham Many and others of the Hebrew University. Perhaps the most significant recent development in the field of space-charge-limited currents in solids is the detailed examination of the transient behavior of the current. Dr. Many presented a theoretical analysis of such cases. He pointed out that the drift mobility could be determined from the cusp which appears in the initial transient. Thus, these measurements can be used to determine this parameter in cases where Hall measurements are impractical. In applying this technique to the molecular crystals anthracene and iodine, using photogenerated ohmic contacts, he reported an anisotropic mobility in both crystals. In addition, the hole mobility in anthracene perpendicular to the *ab* plane was reported to follow a $1/T^2$ dependence on temperature. This strongly suggests the applicability of a band model to this crystal. Extremely low trap densities of $10^{12}/\text{cm}^3$ were reported for iodine in contrast to trap densities which are usually two orders of magnitude higher in nonmolecular crystals.

D. Olness, M. Silver, and R. C. Jarnagin of the University of North Carolina also reported on transient space-charge-limited photocurrents in anthracene. Under extremely high-light-intensity flashes of microsecond duration, an initial transient over and above the space-charge-limited photocurrent predicted by Many was reported. The behavior of this transient as a function of intensity, applied field, and crystal thickness for various electrode materials was presented,



Fritz Stöckmann—photo-response of insulators.



Dwight North—noise in insulators.



P. D. Fochs—growth of CdS whiskers and platelets.

and the results suggest either bulk generation of carriers by the fluorescent light or a surface current.

Steady-state space-charge-limited current measurements were used to obtain the effective density of states in the band appropriate to excess hole motion in anthracene by Peter Mark of RCA Laboratories. He reported that the thermal activation energy of the space charge at various voltages corresponded to the quasi-steady-state Fermi level at each voltage for the exponential trap distribution obtained in his crystals. Since physical significance can be attributed to this thermal activation energy, the effective density of states is obtained from these measurements. He reported a value of $(6 \pm 3) \times 10^{21} \text{ cm}^{-3}$ which he pointed out was close to twice the molecular density ($8.4 \times 10^{21} \text{ cm}^{-3}$) and hence strongly indicated that the hole band was at most a few kT wide at room temperature. Data from steady-state bulk current measurements were also presented by George Heilmeyer, George Warfield, and Sol Harrison of Princeton University and RCA Laboratories. They presented the results of such measurements using ohmic contacts on the molecular crystal, metal-free phthalocyanine, which showed that the current increased linearly with voltage up to fields of 10^4 volts/cm and then followed a square-law dependence on field above this value. Measurement of the temperature dependence of the I-V characteristic yielded trap densities of 10^{14} cm^{-3} and depth 0.8 eV below the conduction band if the observed behavior was interpreted in terms of space-charge-limited currents. The low trap density was consistent with that reported on other molecular crystals.

A. C. English of the University of California presented evidence for space-charge-limited current flow in silicon-carbide crystals with tungsten electrodes, and R. H. Tregold of the University College of North Wales reported the results of dc measurements on barium titanate above the Curie temperature, which were interpreted in terms of space-charge-limited currents in the presence of diffusion effects.

David Kahn of RIAS, after discussing some ex-

perimental investigations of photoconductivity in colored alkali-halide crystals with blocking electrodes, proceeded to solve the equations for charge-carrier motion under an applied dc field. His experimental results showed agreement with the theory. The ac case, however, could not be solved exactly for an arbitrary applied voltage, but a third-order harmonic analysis and a difference-equation analogue were discussed by Dr. Kahn. H. Tung Li of the Xerox Corporation developed a theoretical model to account for the observed photo-induced discharge characteristics of amorphous selenium plates. His model took into account not only the bulk trapping of mobile carriers, but also the recombination of the photo-injected carriers. His experimental results showed good agreement with the theory, and a hole-trapping range of $8 \times 10^{-8} \text{ cm}^2/\text{V}$ and recombination lifetime of 10^{-9} sec were found. The agreement of these values with those obtained by conventional pulse techniques was suggested as confirmation that the work of Dr. Li provided a new method for measuring these two parameters in a photoconductor.

Henry Seiwatz of the Armour Research Foundation discussed a technique for measuring the instantaneous space-charge depth in an insulator. Using a guarded parallel-plate capacitor consisting of a layer of thin insulator film and a thick gas gap, a Townsend discharge was induced in the gas gap, while a voltage ramp was applied to the capacitor. A measurement of the capacitance under these circumstances yielded simultaneous values of the charge density per unit area in the film and the potential difference across the film. Since the latter quantity is proportional to the average dipole moment per unit area, the average charge separation in the film is determined. Preliminary measurements on MYLAR films were presented which indicated that a space-charge depth of several percent of the thickness was obtained in one second or less at field well below breakdown.

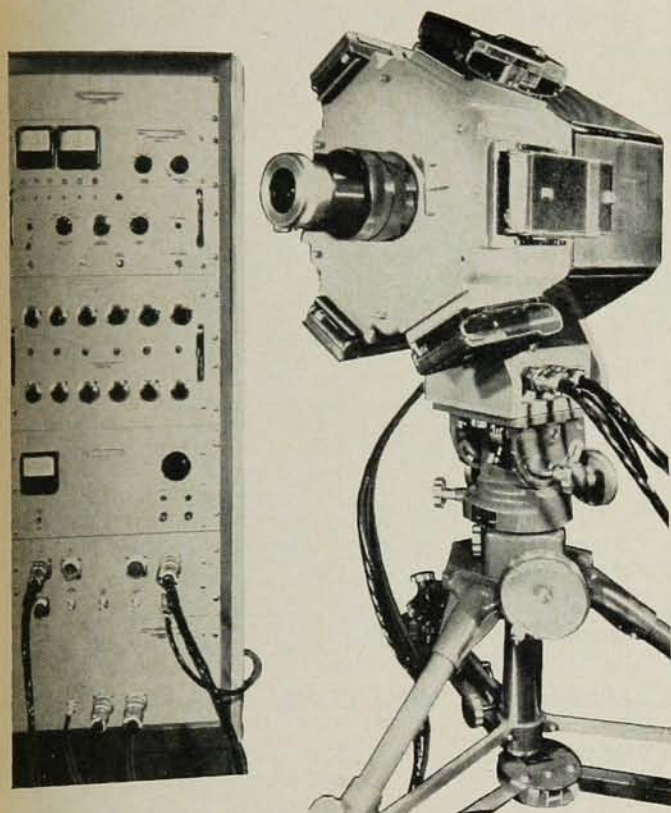
Space-charge-limited currents in vitreous selenium films were used to determine the trap distribution in this material by Dr. Lanyon of the University of Illinois. He related the experimentally found exponential trap distribution for holes to the relatively slow variation of the absorption coefficient with photon energy on the long-wavelength side of the absorption edge, which has been observed by many workers.

Albert Rose of RCA Laboratories presented another paper in the Rose and Lampert series studying all facets of space-charge-limited current flow in solids. This paper, entitled "A Comparative Anatomy of Double-Injection Models", described in simple physical terms the wide spectrum of double-injection work done in the last fifteen years. Another paper on the theory of double-injection current flow was presented by Fritz Stöckmann of the University of Karlsruhe. Prof. Stöckmann correlated saturated photocurrents with double-injection space-charge-limited currents and analyzed the photoresponse for each case of double-injection current flow considered by Rose and Lampert.



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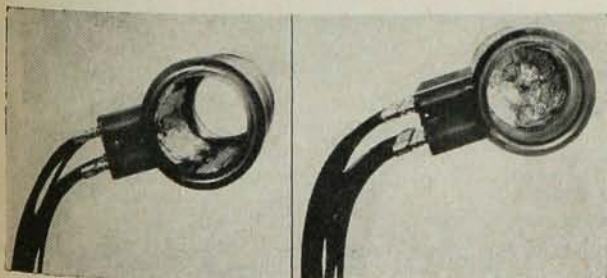
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DWIGHT O. North, also of RCA Laboratories, had the dubious honor of starting the evening session with a theory paper pitched towards a tired, well-fed group of experimentalists. Dr. North succeeded, however, with a very interesting presentation of work on an equivalent circuit to represent noise processes in nonmetals. The paper outlined what Dr. North calls his "do-it-yourself kit", with which an experimentalist can estimate the effect of noise in his system.

Several papers were presented which discussed the effects of high internal fields in insulators. Dr. Roland Smith of RCA Laboratories described pulsed-conductivity experiments with CdS crystals in which the current and voltage are linearly related up to the fields at which the electron drift velocity reaches the sound velocity in the crystal. Above this voltage the current saturates. Dr. Smith discussed a model to describe this effect in terms of piezoelectric coupling between the lattice waves and the electron stream similar to that described by Hutson at the 1961 Photoconductivity Conference.

Wolfgang Ruppel of the University of Karlsruhe discussed the similarity between the anomaly in the photovoltaic response of CdS and ZnS. Dr. Ruppel then presented a model to explain this response and in particular the abrupt sign reversal and unusually high photovoltage in ZnS. Karl Böer of New York University presented the latest in his interesting series of movies based on the field and temperature shift of the absorption edge of CdS. In addition to tracing the motion of high-field regions through CdS crystals, Prof. Böer was able to use his technique to show the growth of regions of high local heating.

A fascinating motion picture illustrating the growth habits of CdS plates and whiskers was shown by P. D. Fochs of the Associated Electrical Industries in Harlow, England. Dr. Fochs described the apparatus he used for the growth of platelets from the vapor phase, which are especially well suited for space-charge-limited current studies. Another contributor from England, Walter Spear of the University of Leeds,

described the first drift-mobility studies of hole transport in undoped CdS crystals. Using an electron-bombardment technique, Prof. Spear was able to study the motion of both holes and electrons in CdS. He reported shallow electron traps presumably associated with sulphur vacancies and a hole mobility which is an exponential function of inverse temperature. Prof. Spear ascribed the temperature dependence to the same complex valence-band structure that Balkanski has proposed to explain the dichroic nature of the absorption band. The values of electron and hole mobility obtained by this technique are in good agreement with those obtained from the PEM effect.

Four papers dealt specifically with contacts and the use of contact effects in the study of dielectrics. G. T. Wright of the University of Birmingham described the use of space-charge-limited currents to study the contact between CdS crystals and an evaporated gold electrode. He also described some experiments on the thermal release of electrons trapped in these CdS crystals at low temperatures. Prof. Wright also gave further evidence for a very low trap density in his well-compensated samples. Dr. Richard Muller of the California Institute of Technology also discussed the effect of gold blocking contacts made to CdS crystals. Dr. Muller studied the frequency dependence of the depletion-layer capacitance and established a correlation with the shallow traps whose presence was inferred from space-charge-limited current studies on the same samples.

Martin Pope of New York University presented a summary of his work and that of others at NYU on the various electrolytic contacts which one can make to organic crystals. Prof. Pope then discussed the kinetics of charge transport at the electrolyte crystal surface. The fourth paper dealing with the effects of contacts was presented by Peter Warter and George Warfield of Princeton University. Their paper described the dynamics of depletion-layer formation in an insulator exhibiting a long free-carrier range and the use of the transient currents associated with depletion-layer formation to study electron trapping. Experiments of this type using the thermal release of trapped electrons in AgCl crystals were then described.

"All's Well That Ends Well," and the weather at this conference was no exception. As the last session on Friday morning came to an end, the weather made an abrupt change providing ideal conditions for swimming or tennis before departing for home. One wonders whether there would have been the same attentive audiences, had this been the weather for the preceding two days.

Although the self-contained, intimate atmosphere of a resort hotel would seem to be ideal for such a small informal meeting, no meeting can be a success without careful planning. In this respect those who attended the conference are indebted to the organizing committee and, in particular, to Alfred Miller of the State University of New York, Long Island Center, for their careful attention to every detail.