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PHYSICS OF NONLINEAR TRANSPORT IN SEMICONDUCTORS.

Dr. I. Kaufman

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER C-8-79	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PHYSICS OF NONLINEAR TRANSPORT IN SEMICONDUCTORS		5. TYPE OF REPORT & PERIOD COVERED Conference
		6. PERFORMING ORG. REPORT NUMBER C-8-79
7. AUTHOR(s) I. Kaufman		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Office of Naval Research, Branch Office Box 39 FPO New York 09510		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE October 11, 1979
		13. NUMBER OF PAGES 18
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Nonlinear electron transport, Hot electrons, Electronic structure of semiconductors, Electron-phonon interactions, Transport, Carrier-carrier interaction, Non-equilibrium phonons, High magnetic field effects, Noise and diffusion, Optical excitation, Electron devices, Microwave devices, MISFETS, MESFETs, MOSFETs, Two-dimensional systems, VLSI.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is a report on the NATO Advanced Study Institute of Nonlinear Transport in Semiconductors, held at the Sogesta Center near Urbino, Italy, during 16-27 July 1979. The Institute was held to "provide young researchers with the foundations of the principles of nonlinear transport," so that they might meet the challenges of nonlinear transport behavior that will be encountered in work with ultra-fine-geometry or ultra-high-speed semiconductor devices. The topics that were treated include phenomenological aspects of hot carriers, electronic structure and band renormalization,

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electron-phonon interactions, semi-classical and quantum transport, carrier-carrier interactions and screening, non-equilibrium phonon interactions, experimental aspects of hot carrier transport, high magnetic field effects, device effects, noise and diffusion, and optical excitation of hot carriers.

PHYSICS OF NONLINEAR TRANSPORT IN SEMICONDUCTORS

For a number of years now, NATO has sponsored several Advanced Study Institutes (ASIs) each year. These usually are rather high level topical meetings or short courses designed to transfer scientific or technological information throughout the NATO countries and are generally restricted to a very limited number of participants.

Although ASIs have been and are being held in various locations in Northern and Western Europe, one of the more popular locations in recent years has been the Sogesta Center, a modern functional and educational research center located about 4 km from the Italian hill town of Urbino—a name familar to many readers as the birth place of the painter Raphael. The name *Sogesta*, an acronym for Società per Gestire Tecnologia Avanzata (Corporation for Managing Advanced Technology) was indeed chosen appropriately: Sogesta, a company belonging to the ENI group (the Italian National Hydrocarbon Authority) organizes and manages study courses, schools, seminars, and research activities for and in collaboration with ENI and other Italian foreign organizations in its buildings.

The Center itself is a group of very modern, contiguous buildings that house a number of classrooms equipped with audio/visual aids, with capacities of from 10 to 300 persons, a computer center and associated libraries, and a residential area that can house 230 and is complete with a very satisfactory self-service restaurant and other facilities. The computer center itself is in active use by a small group of permanent employees who generate software for ENI (and possibly others).

A great advantage of this facility for holding short-courses is its isolation; for there are no beaches and no casinos to distract from the business at hand. Moreover, since the group in attendance essentially lives together, after-session discussions become the order of the day.

It was this isolation from distraction plus the excellent facilities that prompted the organizers to choose Sogesta as the site for the 16-27 July 1979 NATO ASI on Nonlinear Electron Transport in Semiconductors.

Electrons, of course, belong to that class of particles known as *fermions*. I found it therefore to be an interesting coincidence that Sogesta overlooks the buildings of Fermignano (pronounced fermi-nyano), a town located in the valley about a mile away.

True to the spirit of NATO, the organizers and directors came from several countries: Dr. D.K. Ferry from Colorado State Univ. (US); Dr. J.R. Barker from the Univ. of Warwick (UK), and Dr. C. Jacoboni from the Univ. of Modena (Italy).

The lecturers of the ASI had come from the US, UK, Italy, FRG, Austria, France, and Belgium. There were 69 participants, including the lecturers, with representation not only from these countries, but also from other NATO countries; there was also a representative each from Saudi Arabia and Hungary.

That this was indeed a Study Institute was emphasized by the very full schedule. The lectures of the first week started on Monday at 9 a.m. and concluded at noon on Saturday. The advertised last day for the ASI was Friday July 27th. Indeed, the last speaker finished at 6:35 p.m. of that day.

The purpose of the ASI was to provide a deep basic total picture of the various aspects of nonlinear electron transport in semiconductors. The list of topics addressed included: Phenomenological aspects of hot carriers, electronic structure, electron-phonon interactions, transport, carrier-carrier interaction, non-equilibrium phonons, high magnetic fields, noise and diffusion, optical excitation, and devices.

But why have such a Study Institute at this time? After all, did not most of the researchers in the US stop work on the subject of nonlinear transport during the 60's? What might be the possible application that could merit such a NATO-supported effort "to provide young researchers with the foundations of the principles of nonlinear transport?"

According to the organizers, the chief reason is the progress that is being made toward the ultra-microscopic geometries required for very high speed, very large scale integrated circuits, or for microwave amplifiers.

As an example of the need to look at non-linear transport phenomena, we consider a field effect transistor whose channel is only 1000 Å in length. With one volt applied across its channel, the longitudinal electric field here is 10^7 volts/meter. Already in 1951 Ryder and Shockley had demonstrated carrier velocity saturation in germanium for fields in excess of 10^5 volts/meter; so that the concept of linear transport with drift velocity given by $v_d = \mu F$, where μ is the mobility and F is the electric field, ceased to hold. More drastic than saturation even is the phenomenon of negative differential mobility in gallium arsenide, predicted by Hilsum and discovered experimentally and exploited by Gunn, which occurs with F of around (3) (10^5) volts/meter and is the basis of the well known Gunn oscillator.

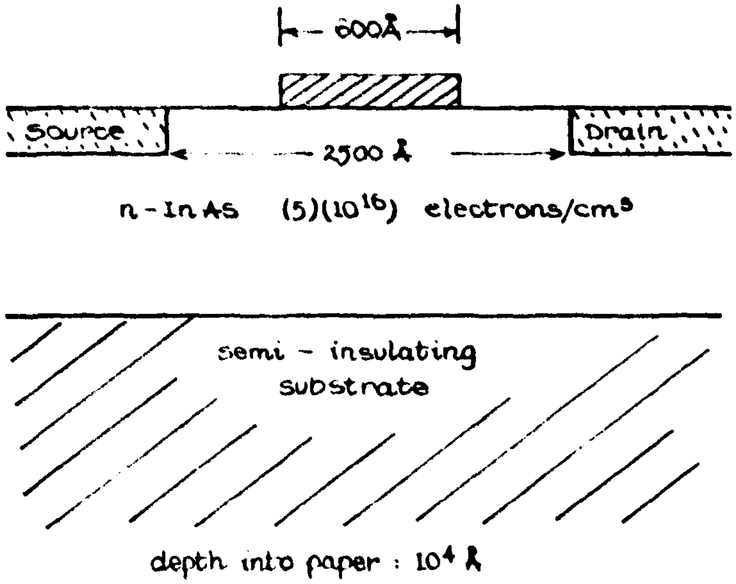
But why not reduce the channel voltage in the example given above, and therefore remain in the linear transport region? Actually, there is a lower limit to electrode voltages that are considered feasible, and this is generally thought to be the voltage corresponding to thermal energy kT (0.026 volts at room temperature). In practice, one likes to have electrode voltages of several times this amount. But even 0.1 volt, or four times the thermal voltage, still leaves us in the domain of nonlinear transport here.

Besides the saturation of drift velocity or the transfer of electrons from one sub-band to another, as in gallium arsenide, other effects occur. Ferry, for example, reported on a simulation study carried out for the field effect transistor shown in Fig. 1(a). Here, based on the geometry of the structure, he had calculated an RC time constant of 10^{-13} seconds. Assuming, as is usually done in the linear domain, an instantaneous relation of $v_d = \mu F$, this would mean that on application of step function source/drain voltage V_D of, say, 0.1 v, the drain current should rise to nearly its final value in about (2) (10^{-13}) sec. According to the simulation study the actual v_d vs. t curve expected for this device (at 77K) is that of Fig. 1(b). In other words, the time required for an electron to reach its final velocity, taking collision processes into account, is about 10 times that expected from the simple RC model.

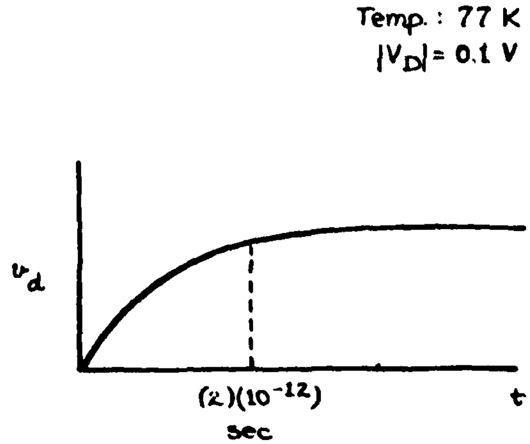
Another problem is that because of the small geometries one can often run into the situation in which the current is carried by only a small number of electrons. One number mentioned at Sogesta was as few as 130 conduction electrons in the channel at any one time. It is not at all clear how small a number of electrons can be tolerated before the conclusions from statistics usually used for semiconductors break down.

Finally, we note that the classical method that has been used for calculating such average electron transport quantities as drift velocity is based on calculations using the Boltzmann transport equation. According to Barker, the use of the Boltzmann equation, with its simple local relative processes implied, fails for electron transport in the high fields associated with ultra-small devices. Instead, calculations should be performed using quantum transport theory. As an example, he mentioned that for devices only 1000-Å long the Boltzmann equation method can give errors of up to 50%.

The reasons given above for justifying the renewed look and the introduction to young scientists of problems dealing with non-linear transport are related to the construction of devices now on the horizon. These are actually not the whole story, however, for there are many other effects that were discussed, both electrical and optical in nature, relating to the behavior of electrons in the nonlinear transport situation encountered in both high electric and high magnetic fields, even though



(a)



(b)

Figure 1:
(a) Geometry of MESFET for Ferry's simulation study.
(b) Drift velocity vs time after source-drain voltage is turned on.

most of these may not have relevance to practical devices at this time. Some, on the other hand, have turned out to be useful during measurement procedures. An example is the Shubnikov-de Haas effect, in which the electron temperature in a semiconductor is found by measurement of the ratio of the amplitudes of oscillation peaks in the fluctuations of magneto-resistance that are seen as the magnetic field is swept through values corresponding to several Landau level resonances. It is for this reason that the ASI covered the broad spectrum of nonlinear transport.

During the last few years there have been several centers or institutes that have been active in the field of nonlinear transport of electrons. Among these are several groups in Austria; North Texas State Univ., Denton, Texas; the Univ. of Warwick, UK; the Université des Sciences et Techniques du Languedoc, Montpellier, France; Colorado State Univ., Fort Collins, Colorado; Cornell Univ., Ithaca, New York; and, for about the last ten years, the Univ. of Modena, Italy. It was quite appropriate therefore that Prof. Carlo Jacoboni, from Modena, present the introductory lecture. Here he briefly discussed the process of electron heating, i.e., the various scattering mechanisms for both polar and covalent semiconductors that lead to electrons being heated above lattice temperature by an applied electric field. He also cautioned against the practice of assigning a specific electron temperature to these hot electrons, since for a number of high field situations the electron distribution ceases to be Maxwellian. Finally, he discussed the general framework of electron transport investigations with the aid of Fig. 2, pointing out that the aim of both theory and experiment is to arrive at the distribution function, i.e., the relative distribution of electrons as a function of energy, momentum, etc., and from this to arrive at such quantities as average electron energy or drift velocity.

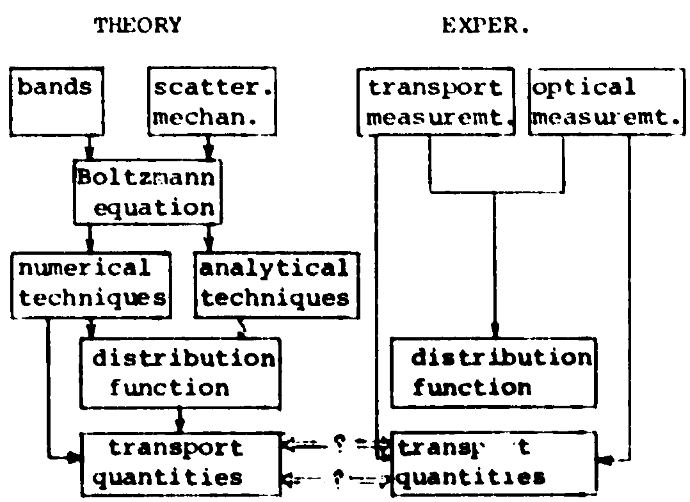


Figure 2

Names and affiliations of the other lecturers and abstracts of their presentations follow:

1. K. Hess (Univ. of Illinois, Urbana, Ill.), "Phenomenological Physics of Hot Carriers in Semiconductors." (Six lectures)

Prof. Hess explained the concept of hot carriers and electron temperature models. He pointed out, for example, that the use of the carrier temperature model for the electron distribution function $f=f_o+f_1$, [where f_o is the Maxwell-Boltzmann distribution function corresponding to carrier temperature T_c; f_1, which is responsible for the current and is small (and odd in k)] holds only for high carrier densities, where carrier-carrier collisions and elastic scattering mechanisms with energy-independent rate predominate. This was illustrated by the following table:

Device	Carrier Density—cm^{-3}	T_c model
MOS	10^{18}	Excellent
Charge Transfer Devices (Gunn Effect)	10^{15}	Not Good
Bipolar Transistor (Bulk)	$>10^{16}$	Good
Bipolar Transistor (Space Charge Region)	10^{8}	Bad
Impatt (Avalanche Region)	$\leq 10^{16}$	Good

The table was also said to reflect to some extent the hot-electron research topics of present interest. These concentrate on finding distribution functions for charge transfer devices and reversed biased diodes, as well as on size quantization, diffusion, nonstationary transfer for MOS transistors, CCDs, etc.

There was emphasis in the lectures on interface effects, hot electron diffusion, and nonstationary transport.

The use of hot electron phenomena as a tool to determine parameters which are important for the band structure and the electron-phonon interaction was discussed.

Detailed consideration was given to the field dependent mobility and the importance of phonon scattering. The general influence of a magnetic field on hot carrier transport was discussed and explicit theoretical results were given for the magnetotransport in two-dimensional systems.

The lectures also dealt with effects peculiar to narrow-gap semiconductors and many-valley semiconductors.

2. C. Calandra (Università di Modena, Italy), "Electronic Structure of Semiconductors."

The objective of these three lectures was to provide an introduction to the topic of electronic structure of crystalline semiconductors. Although designed to emphasize only the basic concepts and the problems whose appreciation is required to understand the behavior of valence electrons in semiconductors, this set of lectures was still, by necessity, highly theoretical. The first portion, which was devoted to the one-electron description of the electronic structure, dealt with the main features of the chemical bond, the mechanism responsible for the formation of the semiconducting phase of the crystal, and the quantities of interest in studying transport properties.

The second part of the lectures dealt with the very complicated problem of many-body interactions. They were designed to illustrate the method of the Green's function for calculation of the self-energy and the problems associated with calculations of modifications in band structure when electron-electron repulsion is allowed for.

Besides exposing participants of the ASI to some of the theoretical techniques needed for these calculation, the presentations brought out the very practical conclusion that the band gap of a semiconductor can be altered appreciably by high carrier density. An example is given in Fig. 3.

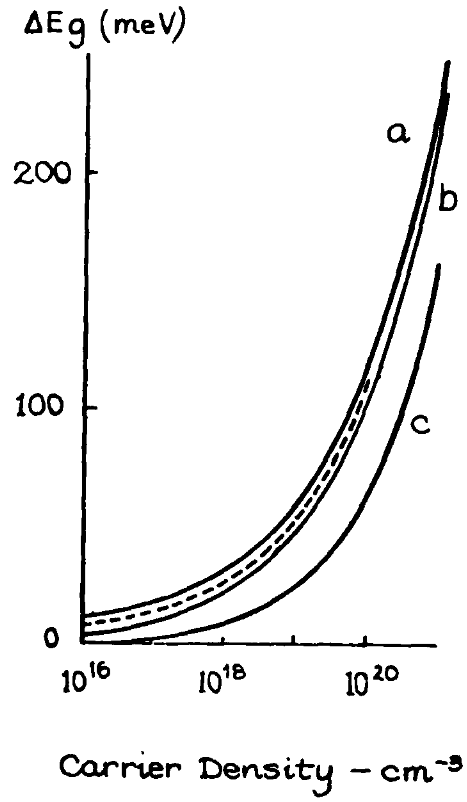


Figure 3

Figure 3:
Theoretical dependence of the gap narrowing (in meV) on carrier concentration for n-type GaAs at T=OK. Dashed line gives the results of a calculation with Lindhard dielectric function. Solid lines: a) results of Thomas Fermi calculation; b) Unscreened exchange contribution; c) ΔE_c conduction band shift.

The curves of this figure should be of great interest to workers performing experiments in which very high carrier densities are generat by such techniques as illumination of a crystal with ultra-short gh energy laser pulses.

3. P. Vogl (Univ. of Graz, Graz, Austria) "The Electron-Phonon Interaction."

Dr. Vogl's three exceptionally well presented lectures dealt with the fundamental aspects of the interaction between electrons and lattice vibrations. In the first part, a survey of the standard types of electron-phonon interactions for acoustic and optical phonons in semiconductors was presented, with emphasis on the physical concepts involved. This was followed by a first-principles approach, in a rigorous, quantum-mechanical framework. Next, practical schemes for computing electron-phonon scattering rates without adjustable parameters, i.e., just from the band structure of perfect crystals, were developed and applied to deformation potential constants. This was followed by a pseudopotential calculation of the polaron coupling constant. Finally, it was demonstrated that the theory that had been developed provides a systematic scheme to include screening, surfaces, and external fields.

Although, according to Vogl, this material can all be found in the published literature, it has possibly never been presented anywhere else in such a unified manner.

4. G. Bauer (Institut für Physik, Montanuniversität Leoben, Leoben, Austria) "Experimental Studies of Nonlinear Transport in Semiconductors."

Prof. Bauer's five lectures were a review of experimental methods for obtaining transport parameters, electron temperatures, and hot electron distribution functions in bulk material in high electric fields, as follows: The determination of transport parameters in the warm and hot electron regime was discussed for dc as well as ac (microwave) electric fields. Bridge methods adapted for pulsed fields, field modulation techniques, and harmonic mixing methods for obtaining the warm electron coefficient β [in $\mu = \mu_o (1 - \beta F^2)$, where μ and μ_o are mobility and F is electric field] were presented, as were µsec and nsec. pulse techniques used for the determination of hot-electron conductivity, Hall coefficient, and magneto-resistance. It was pointed out that time resolved conductivity and Hall measurements are necessary for an understanding of impurity breakdown and avalanche effects, as well as for nonequivalent intervalley scattering effects. Capacitive probe techniques, microwave probe techniques, and ultrashort pulse techniques were discussed in connection with the Gunn effect. Methods for the determination of electron temperatures in high electric fields, including mobility and Hall measurements, Faraday effect, and hot electron birefringence experiments, Burstein-Moss shift of the optical absorption edge and hot electron Shubnikov-de Haas effect were also presented. Optical methods suitable for a determination of nonequilibrium carrier distribution functions discussed were absorption measurements, light emission experiments, inelastic light scattering, and intraband absorption and emission in quantizing magnetic fields.

5. R. Ulbrich (Institute of Physics, Universität Dortmund, Dortmund, Germany) "Optical Excitation of Hot Carriers in Semiconductors."

Dr. Ulbrich, an enthusiastic experimentalist, treated the subject of optical excitation of hot carriers in semiconductors in two lectures. In the realm of optical transitions he discussed band-to-band transitions ("free" electrons or holes), electron-hole pair excitations ("excitons"), and exciton resonances ("polaritons"). Experiments relating to optical spectra (absorption, reflectance, and emission) were discussed for germanium, silicon, gallium arsenide, copper oxide, and other semiconductors. The concept of "semi-empirical" was treated in the context of band structure calculations. Light source requirements in terms of frequency, power densities, and penetration depths for experiments relating to optical injection of e-h pairs were delineated. Specific experiments were discussed, including the optical measurement of an electron distribution function.

6. R. Nicholas (Clarendon Laboratory, Oxford Univ., Oxford, UK) "Hot-Electron Transport in Quantizing Magnetic Fields."

In Dr. Nicholas's two lectures, prepared together with J.C. Portal (I.N.S.A., Departement de Physique, 31077 Toulouse Cedex, France), he summarized results of experiments by a number of investigators involving hot electrons in magnetic fields. Here interesting effects occur because of the quantization of electron energies into Landau levels.

Specifically, Nicholas gave examples of how the Shubnikov-de Haas effect, mentioned earlier, has been used to measure electron temperature. (But he also pointed out that this scheme works only for the case of degenerate semiconductors and, of course, only if the distribution function is Maxwellian, so that a temperature can be defined.)

While this method does not apply to non-degenerate semiconductors, there are a number of other interesting effects. In particular, when the energy relaxation mechanisms are monoenergetic, such as when longitudinal optical phonons are emitted, then a resonant electron cooling can occur when the separation between one or more Landau levels corresponds to the energy of the relaxation process. Examples are the "hot electron magneto-phonon effect" for phonon energies and the new and growing field of impurity level determination by the "magneto-impurity effect."

7. P. Kocevar (Physics Institute, Univ. of Graz, Graz, Austria) presented two one-hour lectures:

(a) "Multiphonon Scattering."

Here Dr. Kocevar discussed the theory of electron-phonon interactions of second or higher order, i.e., scattering processes in which two or more phonons are involved. Conclusions from studies of this subject were as expected, that where the adiabatic principle seems to work well, higher order electron-phonon processes are small compared to first-order interactions for nonpolar lattice modes in the standard semiconducting materials.

Two-phonon processes have so far been most clearly identified only with spectroscopic methods or in the resonant magneto-conductivity effects mentioned earlier. As far as ordinary transport is concerned, there is a possibility of noticeable contribution in n-type silicon, but any conclusive analysis of the electron mobility here is still lacking. Much larger contributions of two-phonon processes have to be expected and have been found in high-field transport, because of their increased importance as energy dissipating mechanisms.

(b) Nonequilibrium Phonon Processes."

The coupled systems of electrons ("e") and phonons ("ph") in a conducting solid will be shifted from their equilibrium distribution under the influence of an external electric field F. Now, the momentum and energy imparted to the carriers by the field cannot be dissipated through "normal" e-e, e-ph and ph-ph-collisions, which conserve the total momentum and energy of the e-ph-system. A steady state can only be established by momentum- and energy-loss mechanisms such as "Umklapp"-processes, in which momentum is transferred to the crystal as a whole, or scattering at the crystal-boundaries, where momentum and energy, predominantly of the phonons, are dissipated into a surrounding "heat bath." Consequently the nonelectronic dissipation mechanisms for non-equilibrium phonons determine the possibility of time-dependent, nonstationary phenomena and can also influence the details of the usually realized steady-state transport. Quite generally one has to expect effects of the nonequilibrium of both the e- and ph-subsystem due to the mutual "dragging along" through collisions in any conventional transport experiment at sufficiently low temperatures in sufficiently pure and perfect materials: "phonon drag" by electrons in the lattice thermal conductivity, "phonon drag" of electrons in the electrical conductivity and both drag effects in the thermopower. Moreover, in semiconductors, under nonohmic conditions, we expect effects of "phonon-heating" by hot carriers.

Whereas many of the other lectures were concerned with "hot electrons," this talk thus dealt with "hot phonons."

Kocevar discussed the three distinct approaches to the description of such nonequilibrium phonon systems: a) The classical approach, or analysis for the "hydrodynamical regime," in which the charge carriers are treated as an ensemble that tends to adapt itself as a whole instantaneously to the electric field as deformation potential induced by an acoustic wave; b) The quantum-mechanical approach, which describes the interaction of carriers with the lattice modes by individual scattering events between electrons and phonons as ballistic particles with a corresponding Boltzmann equation; and c) a unified approach that treats both the wave aspect and the quasi-particle aspect.

Specific points covered were phonon instabilities, phonon lifetimes, steady-state effects of nonthermal phonons, some additional miscellaneous effects, and some spectacular examples of nonthermal acoustic emission.

8. J.P. Nougier (Université des Sciences et Techniques du Languedoc, Montpellier, France), "Noise and Diffussion of Hot Carriers."

In this two-hour presentation Prof. Nougier discussed the work of his group on determination of diffusion coefficients. His abstract follows:

The noise temperature $T_n(V,f)$ is defined through the noise voltage spectral density $S_V(V,f)$ and the differential impedance $Z(V,f)$: $S_V(V,f) = 4k_BT_n(V,f)\ Z(V,f)$ where $Z(V,f) = \delta V/\delta I$. This allows one to determine the noise diffusion coefficient $D_n(V,f)$ of a semiconductor biased by a homogeneous electric field E: $k_BT_n(E)/q = D_n(E)/(dv/dE)$. Measurements can be performed parallel and perpendicular to the electric field, using filtering, quadratic detection and integration. To avoid thermal heating of the samples, measurements must be performed during short pulses, and the analysis must be done at high frequencies. Another technique is to study the spreading of a packet of carriers drifted by the electric field, using a time of flight technique : this gives the spreading diffusion coefficient D_S. Indeed, in the usual operating conditions it can be shown that $D_n = D_S$, and the two techniques are quite complementary. From the theoretical point of view, D(E) can be determined using numerical solutions of the Boltzmann equation. Two kinds of techniques are now available and quite powerful: the Monte Carlo technique and iterative techniques. Such experimental and theoretical determinations are useful both for fundamental physics (study of the interactions, of the coupling constants, of the nonparabolicity factor ...) and for applied physics (device modeling), once the local noise sources are known.

9. C.J. Hearn (Marine Sciences Laboratory, Gwynedd, UK) presented two one-hour lectures:

(a) Carrier-Carrier Interactions and Screening.

This talk was concerned with the role of intercarrier scattering in hot carrier systems, treating the theory of the intercarrier interaction, that of the "critical concentration," and the carrier distribution functions.

As developed by Dr. Hearn, it was shown that intercarrier scattering within a band acts to drive the carriers towards a displaced Maxwellian distribution. In so doing it alters both the energy distribution and the angular distribution in momentum space. Hence one can recognize two facets of the scattering: Momentum transfer and energy transfer between the carriers. In low-field transport the momentum transfer influences the mobility in an indirect manner by altering the angular distribution, and this changes the momentum loss to the lattice by the other scattering mechanisms. This effect is important at high carrier densities and its presence should be signalled by a dependence of mobility upon density, but in practice it is necessary to allow for accompanying changes in other factors, such as impurity scattering. If there are several species of carrier, momentum transfer by interband scattering will occur, and this has a direct effect upon mobility because of the difference in effective mass of the interacting carriers. For example, in electron-hole scattering, momentum is usually lost from the electrons to the holes in a manner similar to the momentum loss to stationary ionized impurities. This topic of intercarrier scattering in low-field transport had been extensively explored by the early 60s.

The energy transfer between carriers is relevant to hot carrier problems and tends to become significant at lower densities than momentum transfer, because acoustic phonon scattering is very nearly elastic and is therefore a far more efficient process for momentum loss than for energy loss, and impurity scattering is entirely elastic. Hearn discussed the calculation of the critical concentration above which intercarrier scattering can be expected to influence the energy distribution of the carriers. Since one is dealing with an essentially Coulombic interaction, the energy transfer rate will be greatest at low carrier energies and it is here that the lattice scattering is weakest. Thus the critical concentration becomes lowest for carriers which are only moderately heated in low temperature samples. This corresponds to a typical situation for photexcited carriers and one can therefore expect intercarrier scattering to have a significant effect on some part of the photocarrier distribution. For the usual high-field experiments conducted at higher temperatures, the critical concentration tends to be above the concentrations that are normally employed and intercarrier scattering is therefore of only marginal importance.

(b) "Theoretical Concepts of Photoexcited Hot Carriers."

This talk treated the photoexcitation into the conduction band of carriers and the resulting heated carrier distributions that occur when the photon energy exceeds the bandgap and the recombination lifetime is much shorter than the time to thermalize with the lattice. Starting with the steady-state Boltzmann equation modified to include recombination and quantum terms, several cases were treated: (1) Photoexcited holes in Cu-doped germanium; (2) Monochromatic excitation of carriers; (3) Effects of optical phonons; (4) Nonlinear effects. It was stated that optical heating of carriers should be a useful investigative tool for probing the electron-phonon interaction, because of the possibilities of choosing different optical excitation spectra and varying the recombination lifetime by preparing samples with different doping concentrations.

10. D.K. Ferry (Colorado State University, Ft. Collins, Colorado, USA) "Semi-classical Transport Theory in Semiconductors." (1 hour).

This presentation was concerned with methods of solving the Boltzmann transport equation (BTE):

$$\frac{\partial f}{\partial t} + \vec{v}\cdot\frac{\partial f}{\partial \vec{r}} + e\vec{F}\cdot\frac{\partial f}{\partial \vec{p}} = \int d\vec{p}\,' \left[f(\vec{p}\,') - f(\vec{p})\right] W[\vec{p},\vec{p}\,']$$

where $f(\vec{r}, \vec{p}, t)$ is the carrier distribution function; $\vec{v}$ the velocity; $\vec{F}$ the electric field; $\vec{p}$ the momentum; and the term on the right the collision turn. Ferry noted that even though in the quantum-mechanical representation $\vec{p}$ becomes $\hbar k$, the equation still remains quasi-classical, as long as collisions are considered instantaneous in both space and time. He then referred to the use of the displaced, or drifted Maxwellian distribution

$$f(E) = A \exp\left[-(E - \vec{v}_d\cdot\vec{p})/kT_e\right]$$

which Frönlich had justified for carrier concentrations above a critical value. (Here E is energy; T_e the electron temperature.) The advantages of implicitly assuming a drifted Maxwellian are that the technique results in simple dynamic equations which give good representation of transient processes and that are well suited to the investigation of synergetic effects in coupled or distributed devices.

Next he outlined the method of moments for the BTE, which results in such measurable quantities as drift velocity, average rate of energy loss to the lattice, and average rate of momentum loss to the lattice.

As an illustration of these techniques, he sketched the procedure from which it was found that for GaAs at 300 K, under application of a step function field of 10 kv/cm, the energy relaxation time considerably exceeded the momentum relaxation time, so that an overshoot of drift occurs.

The rest of the presentation dealt with iterative and Monte Carlo methods of solving the BTE.

11. J.R. Barker (Warwick Univ., Coventry, UK), "Quantum Transport Theory." (1 hour).

Barker, a theoretical physicist, took as the motto of his presentation the quotation from Leonardo da Vinci: "Nessuna humana investigazione si pio dimandara vera scienzia s'essa no passa per le matematiche dimonstrazione." (Liberally translated: "No human investigation can be considered true science unless it can pass mathematical verification.")

And, indeed, Barker's talk, though aimed at understanding and improving devices, was highly mathematical. He discussed non-linear transport from the standpoint of non-equilibrium quantum statistical mechanics by (1) reviewing the underlying concepts of the semi-classical picture and their generalization; (2) discussing the general features of quantum kinetic theory; and (3) describing some many-body aspects of high field transport in the fully coupled electron-phonon -impurity system, including a description of the non-equilibrium screening problems.

Barker noted that these methods of analysis, though conceptually much more difficult than the solution of the BTE, may be necessary, since the latter neglects (1) non-locality of scattering processes; (2) strong driving forces; (3) strong scattering; (4) dense systems—here a single carrier description fails; (5) small systems, where size quantization or surface limited transport becomes important; and (6) nonclassical influence of driving fields, which could lead to Stark or Landau quantization of the electronic states.

12. A. Smirl (North Texas State University, Denton, Texas), "The Physics of Nonlinear Absorption and Ultrafast Carrier Relaxation in Semiconductors." (1 hour).

In this presentation Prof. Smirl discussed the method of using picosecond optical techniques to measure the nonlinar, nonequilibrium optical properties of semiconductors, in an effort to obtain information concerning ultrafast carrier dynamics of high optically-created carrier densities. Such measurements are feasible because it is now-possible to produce intense single laser pulses with peak power of approximately 10^8 watts and of picosecond duration, by using a mode-locked laser together with an optical modulator that selects only one pulse.

Smirl reviewed some of the phenomena and the experimental techniques (and possible artifacts), then centered his discussion on results and interpretation of a single "excite and probe" experiment with 1.06 μm radiation in germanium.

13. D. Calecki (L'Ecole Normale Supérieure, Paris, France), "Hot Electron Distribution Function in Quantizing Magnetic Fields." (1 hour).

In this presentation Dr. Calecki discussed theoretical methods and the use of quantum mechanical formulation for finding the electron distribution function and relaxation times for semiconductors in strong electric and magnetic fields, for both parallel and crossed field cases. For example, he presented a treatment of the steady state solution of the Master Equation, the extreme quantum limit case, the case in which several Landau levels are occupied, and the case of the extreme quantum limit in the situation where electrons interact with non-polar optical phonons.

As a general comment on problems of this kind, Calecki discussed the difficulty of performing rigorous analytical calculations and suggested that the field is open either to very crude approximations with qualitative deductions, or to numerical investigations based on Monte Carlo methods.

14. H. Grubin (United Technologies Research Center, East Hartford, Conn.), "Hot Electron Effect in Semiconductor Devices." (1 hour).

The semiconductor devices discussed principally by Dr. Grubin are those exhibiting transfer of electrons from one valley of an E vs. $\vec{k}$ dispersion curve to another valley, as is known to occur in the Gunn effect. His chief thesis was that the usual velocity-field curve obtained for steady state conditions and spatially uniform fields is not necessarily applicable to the transient, or operating situation. An example given was that for which momentum scattering time is much shorter than energy scattering time, resulting in drift velocity overshoot in time. (This was also discussed by Ferry.)

Another example of overshoot occurs with rapid spatial electric field changes. A third nonlinear effect is seen in the travelling accumulation layer in Gunn devices, in which a travelling accumulation layer segregates the electrons into two classes and causes a rapid fall of field—much more than expected.

Grubin stated that it is not yet clear what influence these effects will have in small-geometry devices; but that it is clear that it is incorrect to try to discuss the behavior of very small, highly doped devices without examining transient relaxation phenomena.

15. N. Reggiani (Institute of Physics, Univ. of Modena, Modena, Italy), "Time-of-Flight Techniques." (1 hour).

Dr. Reggiani reported on the time-of-flight measurements that have been in progress using the 40-keV pulsed electron accelerator of the Univ. of Modena. Here electrons bombard one side of a semiconductor specimen that has an electric field impressed on it, to create electron-hole pairs. One type of carrier is immediately swept to the front; the other type drifts across the specimen. An analysis of the induced current signal results in information on drift velocity and diffusion coefficient.

The speaker elaborated on the details of the technique, some additional information obtainable, conditions to guard against, and comparisons with other methods such as measurement of diffusion coefficients by the "white noise" technique.

In addition to the formal lectures outlined above, there were a number of scheduled seminars, as follows:

1. L. Reggiani, "Hot Holes in Semiconductors."

2. H. Kahlert (Boltzmann Institute, Vienna, Austria), "Nonlinear Transport in One-dimensional Conductors."

Dr. Kahlert reported on recent work aimed at establishing the mechanisms underlying the large differences in conductivity for two directions of such single crystal materials known as TTF-TCNO, KCP, $NbSe_3$, and the polymers polysulfur nitride and polyacetylene.

3. L.D. Laude (Université de L'Etat a Mons, Belgium), "Optical Absorption of Solids under Laser Irradiation."

The speaker reported on work carried out in connection with studies of laser-induced nucleation in solids. It is thought that when solids are irradiated with strong laser light, the band structure is changed by the extra potentical of the light. As a result, the optical absorption curve is altered.

4. A. Smirl, "Saturation and Picosecond Decay of Optical Absorption."

5. F. Koch (Physics Dept., Technische Universität München, Garching, Germany), "The Quasi-two-dimensional Inversion layer."

Dr. Koch reviewed some of the interesting quantum effects found in the very narrow inversion layer of a MOSFET. This medium is of interest since its ultra-thin dimension makes it a quasi-two-dimensional system.

6. H. Grubin, "Device Modelling."

The emphasis here was on gallium arsenide devices—both Gunn devices and FETs. Both theoretical work (solutions of Boltzmann equation) and practical considerations (contacts) were discussed.

7. J.R. Barker and D.K. Ferry "Small Device Modelling."

As mentioned in an early part of this report, VLSI and the subsequent submicroscopic geometries will bring in a number of problems that will not permit simple scaling down of devices. It will be necessary to understand the physics associated with such ultra-fine geometries. A number of the problems were mentioned.

SUMMARY

As has been the practice with other Advanced Study Institutes, the written text associated with the lectures (though not the seminars) is to be published by Plenum Press as Proceedings of this ASI, in 1980.

Although not mentioned earlier in this report, readers will wish to know that a number of the speakers referred to the well-known work of Conwell on nonlinear transport time and again. The reference is E.M. Conwell, *High Field Transport in Semiconductors*, *Solid State Physics*, Supplement 9 (edited by Seitz, Turnbull, and Ehrenreich), Academic Press, N.Y. (1967).

In summary, it can be stated that the organizers put together a most comprehensive package that covered the field quite throughly, so that anyone who was in attendance or those who will ultimately read the Proceedings are or will be well informed of the many aspects of this subject. This does not mean that the persons who attended the ASI and were exposed to this subject for the first time could become experts within the brief two-week period or, for that matter, that the majority could follow the lectures dealing with theoretical topics to any great degree, for the material really came at a fast and furious pace. This ASI, indeed, justified in being an advanced study institute. In fact, it was easy to observe that nearly all the questions during the lectures were asked by individuals who had been working in the field for some time, i.e., by other lecturers. Despite strong encouragment by the directors, there were very few questions asked by the "students." Nevertheless, I believe this ASI should indeed be deemed worthwhile, for it was an excellent introduction to an interesting subject that can become the basis of much additional important work for both theorists and experimenters.