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ELECTRON-PHONON INTERACTIONS IN SEMICONDUCTORS: PHONON TRANSPORT AND DECAY

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Abstract.- Stationary charge transport in semiconductors implies steady flow of directed momentum and excess energy from the coupled system of electrons and phonons to the external heatsink. This article will survey recent developments in phonon spectroscopy with special reference to those phonon transport and decay processes which are directly related to hot electron transport in semiconductors.

1. Introduction

Stationary charge transport in a semiconductor requires transfer of momentum and energy from the system of mobile carriers to the lattice, and then to the crystal boundary, i.e. the external heat reservoir. This irreversible transfer of directed momentum and excess energy is mediated through a variety of lattice vibrational modes. Different electron-phonon interactions (including electron-impurity scattering) and, equally important, phonon-phonon-, Umklapp-, and boundary-scattering provide the microscopic basis for charge transport in the coupled system of electrons, phonons and the heatsink [1].

In typical semiconductors with electron drift mobilities ranging from low $10^2 \text{ cm}^2/\text{Vsec}$ to high $10^6 \text{ cm}^2/\text{Vsec}$ the electron quasi-momenta which play a role, for instance, in low-field transport at low temperatures are quite small. As a consequence, only small-wavevector (i.e. low-energy) acoustical and small-wavevector optical phonons are primarily coupled to the electrons. (We assume for the moment only single-phonon scattering). The subsequent phonon-phonon interactions, however, will bring much more phonon modes (e.g. large-wavevector acoustical phonons) into play. Their characteristics may ultimately determine the overall charge transport properties.

In this article we will survey very recent developments in phonon spectroscopy with special reference to non-equilibrium phonon trans-
port and decay processes which are relevant for carrier transport under "hot electron" conditions in semiconductors. Of central importance is, of course, the knowledge of parameters which describe the various bulk phonon interactions and transport properties: phonon dispersion curves, phonon decay channels, and corresponding scattering rates. Only in a few special cases, however, have phonon relaxation times and their temperature dependence been investigated and reasonably well understood. One is the region of very low energy ($\hbar\omega \ll 1\text{ meV}$) small-wavevector ($q \ll 5 \cdot 10^6 \text{ cm}^{-1}$) acoustical phonons, and the others concern optical phonons with $q \lesssim 2 \cdot 10^5 \text{ cm}^{-1}$. The first case is documented in (meanwhile classical) experiments in the field of ballistic phonon propagation at low temperatures [2]. A variety of dielectric materials, including the technologically important semiconductors has been investigated in the linear dispersion regime at low $T$ [3,4,5]. Strongly anisotropic phonon group velocities and energy flow — the analog of optical birefringence — lead to considerable complications in the treatment of the transport problem, both experimentally and in model calculations [6,7]. Beautiful experimental demonstrations of this so-called "phonon focussing" have been performed very recently [8]. The second case, damping of low-$q$ optical phonons, has been investigated exclusively with optical techniques, mainly light scattering (in the frequency domain), and luminescence and picosecond excite-and-probe in the time domain [9,10].

Only sparse experimental information exists on most other dynamical properties of the phonon system in semiconductors: almost nothing is known on the lifetimes and decay channels of "hot", non-equilibrium phonons away from $q \ll 0$, with energies $\hbar\omega \gtrsim 1\text{ meV}$.

2. Phonon Detectors Existing phonon detectors can be classified in four categories: (1) Use of phonon side-bands in real electronic transitions (e.g. emission or absorption of light by impurities or by intrinsic electronic excitations). Here the electron-phonon coupling is used in situ to convert phonon frequencies to more readily accessible optical frequencies, where one-quantum-detection is, in principle, feasible. A bound exciton line strongly coupled to acoustical phonons has been used successfully to probe phonon distribution functions for $0 < \hbar\omega < 2\text{ meV}$ in CdS [11,12]. Also rare earth ions in alkali halides have been used as efficient spectrometers [13,14]. A disadvantage is, however, the necessity of introducing relatively high impurity concentrations in the crystal, which might disturb the phonon processes under investigation.
A variant is the use of shallow bound impurity electrons in the "reverse capture" configuration: absorption of phonons by resonant intra-impurity and/or impurity-to-continuum transitions can be detected as mobile electrons are released.

(2) Use of phonon side bands in light scattering (Raman-, Brillouin-scattering). The anti-Stokes spectrum contains direct and easily extractable information on the occupation number of optical and acoustical phonons in a relatively restricted, small wave-vector interval centered around \( q=0 \) [15]. An application was the detection of hot, non-equilibrium LO-phonons generated in the process of hot electron energy relaxation [16].

(3) Calorimetric devices deposited on the crystal surface. The most sensitive are thin film bolometers which utilize the normal-to-superconducting transition and are capable of detecting phonon fluxes with a noise equivalent power of \( <10^{-15} \text{ W/Hz} \).

(4) Superconductor-insulator-superconductor tunnel diodes evaporated on the crystal surface. The strongly selective phonon absorption in these devices (through Cooper-pair breaking) is used for detection of phonons with energies \( 2\Delta \), the superconducting gap energy. Variants of this method have been developed for specific purposes. Device principles and ultimate sensitivity are described in Ref. 5.

3. Electron-Phonon-Interaction Those interactions between free carriers and single phonons which are well-known cover only a small wave-vector range, \( q \approx 0 \). Coupling strengths and corresponding energy relaxation rates for a priori given (i.e. assumed) carrier and phonon distributions can be readily calculated [17]. Modifications of the interactions due to screening — which are necessary for the polar acoustic and optic coupling for carrier densities above \( 10^{17} \text{ cm}^{-3} \) — have recently been incorporated [18,19].

The reverse process, i.e. the energy loss (resp. absorption) of phonons through excitation of free electrons and holes has been studied recently in the electron-hole liquid formed under appropriate optical excitation at low temperature in Ge [20]. In the same system the anisotropic phonon propagation and e-h-droplet-phonon interaction has been demonstrated in nice experiments [21].

Coupling between localized electrons bound to impurities or crystal defects is much less understood. Capture of free carriers
into impurity levels via multi-phonon emission has been studied ex-
tensively [22].

4. Phonon Decay For simplicity we will discuss only the key
features of anharmonic phonon decay and the exper-
imental facts known up to now.

4.1 Optical phonons. For optical phonons the only available infor-
mation on lifetimes $T_1$ and $T_2$ (describing
number and phase relaxation) is that of light scattering and fluo-
rescence experiments: from Raman scattering spectra one can directly
determine linewidths of LO and TO Stokes lines[9]. These linewidths
set, from uncertainty principle, a lower limit to the lifetimes $T_1$, $T_2$.
Mooradian reported $\tau_{LO} \geq 28$ psec at $T = 10$ K and $\tau_{LO} \geq 1.3$ psec
at 300 K in GaAs and similar values for Si[9]. Later experiments
on TO phonon-polariton lifetimes in GaP and recently performed pico-
second excite-and-probe experiments confirm the light scattering
data in the time domain [10].

The basic mechanism for optical phonon decay via three-phonon
processes has been treated by Klemens[23] and Orbach[24]. In the
diamond and zincblende semiconductors only anharmonic decay into
two LA phonons is energetically possible. The available combined
density-of-states on the LA branches is not very high. Knowledge of
Grüneisen constants allows the calculation of $\tau_{LO}$ with an order-
of-magnitude agreement with experiment.

4.2 Acoustical phonons. Lifetimes and propagation of acoustical
phonons with high frequencies, $\nu \geq 10^{12}$ Hz
(resp. $E \geq 4$ meV) have been studied up to now only in few cases:
Piezo-electrically excited TA phonons in quartz were reported to
travel ballistically several mm at frequencies up to $2.5 \cdot 10^{12}$ Hz[25].
No further experiments in quartz have been reported, however.
Studies of ballistic, dispersive transport of high-frequency
($\nu \simeq 1.5 \cdot 10^{12}$ Hz) TA phonons generated in the process of non-radia-
tive recombination of e-h-pairs in the model semiconductors GaAs
and InP have recently lead to clear evidence that near-zone-edge
TA phonons can have extraordinary long lifetimes, $\tau_{TA} \geq 10^{-6}$ sec
and do not show appreciable isotope scattering[26].
Observations made in InSb [27] and TlCl [28] seem to indicate that
there is a general trend: at low temperatures the lowest TA branch
phonons have long lifetimes of the order of $10^{-6}$ sec!
4.3 Localized states. In the process of non-radiative recombination of e-h-pairs via deep levels the initial electronic energy is transferred almost completely into zone-edge TA phonons [26]. These phonon modes act then as an energy bottleneck and decay relatively slowly via mode-conversion into LA phonons and subsequently by anharmonic decay into low-energy ($\hbar\omega < 4$ meV) LA and TA modes. Apart from the above discussed LO phonon cascade mechanism[24] there might be also direct vibronic coupling of deep centers with zone-edge TA phonons. The local lattice distortion around defects can induce strong, selective coupling to specific modes in the phonon spectrum. There are first fruitful applications of phonon spectroscopy in the context of non-radiative recombination via capture into deep traps [29]. Selective near IR optical excitation of localized electronic levels combined with simultaneous spectroscopy of lattice relaxation phonons launched into the bulk crystal offers great potential for the investigation of deep level vibronic coupling.

5. Phonon Transport Energy transport in the phonon system is determined by phonon lifetimes and group velocities $v_g$. In typical semiconductors (group IV, III-V) the optical phonons generally do not exceed $v_g \simeq 1.5 \cdot 10^5$ cm/sec and $\tau \simeq 30$ psec. As a result the mean free paths are smaller than 500 Å. Typical acoustical phonon group velocities range from $1 \cdot 10^5$ to $5 \cdot 10^5$ cm/sec for energies below 4 meV. They decrease to zero at the zone boundaries. With momentum relaxation times of $10^{-9} \ldots 10^{-6}$ sec (and even longer at lower energies) one finds mean free paths from $\simeq 10^{-4}$ cm to $10^{-1}$ cm.

The problem of coupled electron-phonon transport has been treated theoretically [30]. Characteristic time constants in the $10^{-6}$ sec range were found from the coupled rate equations under conditions of warm electrons in n-InSb. By far the most exciting aspect of the coupled system is the chance of getting phonon inversion and stimulated phonon emission in electrically or optically pumped configurations [31].

6. Conclusion Only few aspects of the kinetics of the coupled system of electrons and phonons have been sketched in this survey. Many more facets exist. It is clear that — apart from
electron-phonon coupling — much has still to be learned about anharmonic phonon decay. Inherent limitations of the conventional experimental techniques in phonon spectroscopy — spatial and temporal resolution — can possibly pushed down to the pm and psec limits with the implementation of optical techniques at hand.

References

1. A good survey on non-equilibrium phonon processes related to electrical transport was given by:  

2. Closely related is the behavior of thermal conductivity as a function of temperature. It is the equivalent of the backbone of electrical transport, electrical conductivity resp. mobility in the ohmic regime.


15. Overtone Raman spectra (i.e. the coupling to more than one phonon in the scattering event) give access to large wavevector phonons; see, e.g. R.Trommer, M.Cardona, Phys.Rev. B17, 1865 (1978).


18. P.Vogl, ibid. (ref.1) p.75.


30. See the list of references given in Ref.1.