Scattering in Bloch Oscillations in a One-dimensional Quantum Dot Superlattice

by **S.K. Lyo**

Motivation—One of the most fascinating phenomena in solid-state physics is the so-called Bloch oscillations (BOs) with many far-infrared device applications. In 1928, Felix Bloch (1952-Nobel Prize) proposed that electrons in a lattice undergo periodic oscillations in real as well as momentum space in a high electric field without scattering. Unfortunately, the BO period is much greater than the scattering time in natural conductors. Thus BOs have not been realized until the recent fabrication of superlattices which cause the formation of minibands and small Brillouin zones, yielding BO periods shorter than electron scattering times. It is necessary to study this in detail.

Accomplishment—We have solved two models of the Boltzmann transport equation for the nonlinear current of an electron gas in a one-dimensional miniband using a tight-binding model as a function of the time. The first model assumes a constant relaxation time for inelastic (electron-phonon) scattering, while the second model treats electron-phonon scattering exactly (*i.e.*, microscopically). An arbitrary potential for scattering from the impurities is assumed in both cases. The first model is solved analytically, yielding exact transparent results for the first time for the time-dependent current as a function of the elastic and inelastic scattering rates shown in Fig. 1(a). The results show, surprisingly, that the threshold for the onset of the BOs depends only on the elastic scattering rate but not on the inelastic scattering rate. Furthermore, the steady-state current that sets in after a time longer than the scattering time depends on the elastic and inelastic scattering rates in a very different way as shown in the I-V curve in Fig. 1(b) for a short-range impurity potential. For example, the current in the negative differential conductance (NDC) regime of the field E (> 30 V/cm) depends only on the inelastic scattering rate and the dependence is linear. Important quantities in this I-V curve are the peak current I_p and the field E_p at the peak. These quantities satisfy different scaling relationships with the elastic and inelastic scattering rates. Our result also yields an exact time development of the distribution function f(k,t) shown in Fig. 2 as a function of the wave number k. Here, f(k,t) is a Fermi-Dirac function at time t = 0, when the DC field is applied and approaches a non-equilibrium steady state at a long time t > 100 picoseconds after several BOs.

The purpose of the second microscopic model is to check the predictions of the first exact result. This model was solved by developing a purely numerical method which solves the time-dependent Boltzmann equation self-consistently to an arbitrary accuracy. This approach yields accurate numerical results but does not reveal salient underlying physics by itself. We compared the exact scaling relations for I_p and E_p obtained from the first model with these purely numerical results and found good agreement.

Significance—Our exact results yield clear insight into how the field-driven electron oscillation competes with elastic and inelastic scattering to produce BOs for the first time. The results can be used to improve the NDC properties (e.g., peak current and field) by adjusting elastic and inelastic scattering rates.

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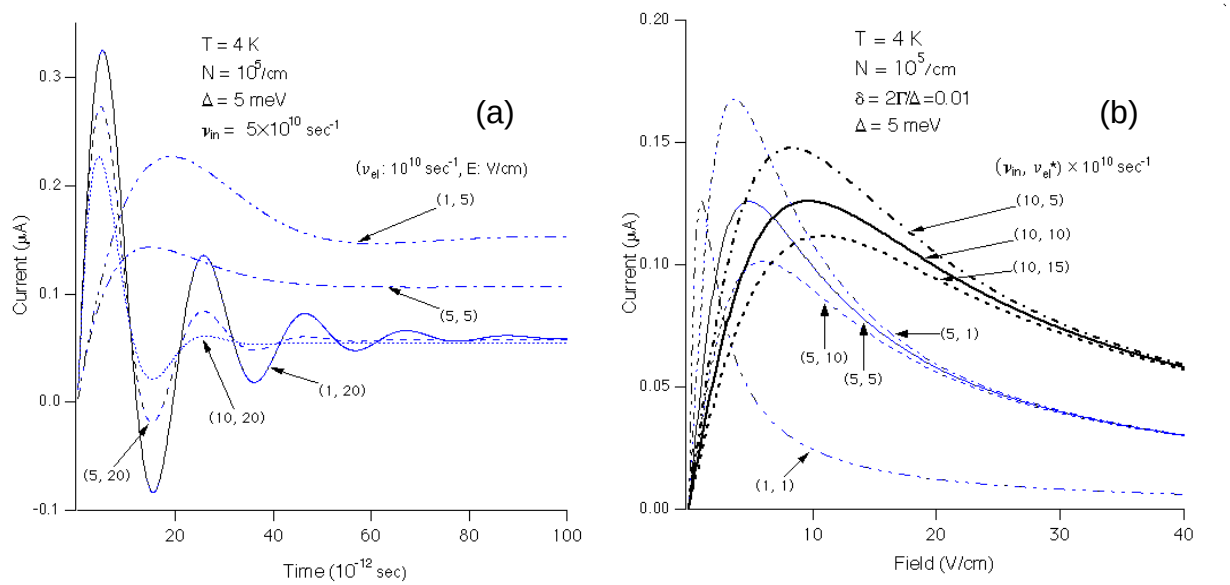

Figure 1. (a) Time-dependent currents for several sets of elastic scattering rates n_{el} and fields E for a fixed inelastic scattering rate n_{in}, band width D, electron density N, and temperature T. (b) Steady-state I-V curves for short-range impurity scattering for several sets of inelastic (n_{in}) and elastic scattering rates. The quantities G and n_{el}^* are level damping and the elastic scattering rate at the band center.

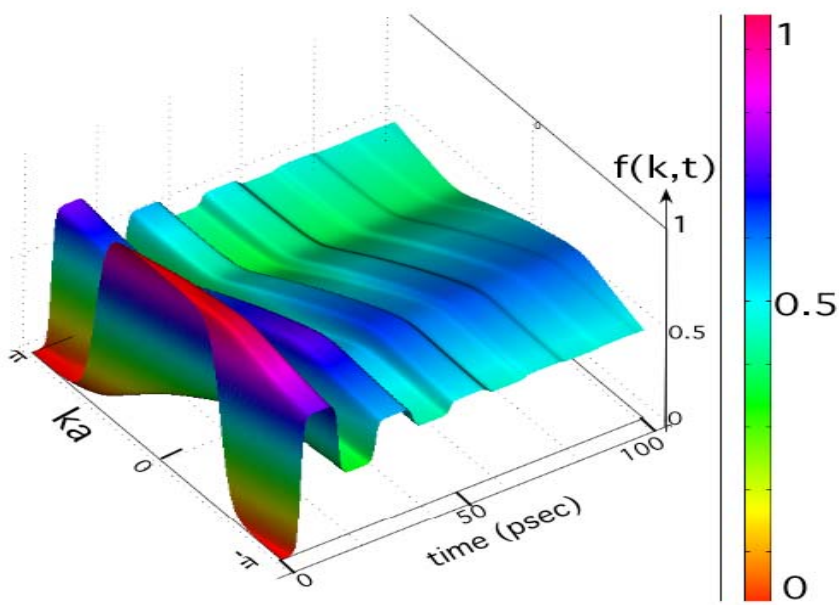

Figure 2. Time development of the distribution function f(k,t) for a one-dimensional superlattice with period a = 100 nm for an electric field E = 20 V/cm and inelastic and elastic scattering rates n_{in} = 5310^{10}/sec, n_{el} = 10^{10}/sec. Here, k is the wave number. Other parameters are the same as given in Fig. 1(a).