Miniband quantum transport in semiconductor nanodevices under broadband illumination

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Abstract. A general theoretical framework for the modelling of miniband transport in semiconductor nanostructures under broadband illumination is presented. Our approach is based on the multi-subband three-dimensional Boltzmann transport equation and allows to investigate both the steady-state and the time-dependent dynamics. The model has been succesfully applied to the problem of the design and optimization of Terahertz quantum well infrared photodetectors and is now applied to a more generic superlattice system. We consider the carrier dynamics in multi-miniband superlattices under black-body illumination showing the existence of regimes in which the current in some minibands is inverted, eventually leading to absolute negative resistance.

Electron dynamics in photoexcited nanostructures has been a matter of intense study for a long time both for the fundamental physical insights that this kind of systems can give and for potential technological applications.

Among others, semiconductor superlattices has received considerable attention as they provide a relatively simple way to build systems in which the band structure of electrons can be precisely determined. This ability, along with the use of optically-active materials, allows to study interesting phenomena regarding the interactions between electrons and light. In particular, superlattices subject to coherent electromagnetic fields, like those typically provided by lasers, have been shown to give rise to a number of interesting phenomena including light-induced absolute negative resistance [1, 2, 3].

On the other hand superlattices subject to an incoherent and broadband photoexcitation rather than a laser source are also interesting as they can be used as a model for state-of-the-art quantum well infrared photodetectors (QWIPs) which basically consist in a sequence of quantum-wells and barriers (comprising many tens of periods) which are then exposed to background blackbody radiation and infrared light emitted by objects. The incoming photons will then promote bound electrons into the continuum which in turn will give rise to a current once the system is properly biased.

In the past we have focused our attention on the development of a general theoretical framework for the simulation of carrier transport photoexcited weakly-coupled superlattices and we have applied it to the simulation and design of a new architecture for THz QWIPs with improved temperature performance [4, 5]. The model is based on the multi-subband three-dimensional Boltzmann transport equation describing the dynamics of the electron population.
Figure 1. Total current as a function of temperature when the device is subject to a positive bias and irradiated with a 300K blackbody. The device shows absolute negative resistance between 5 and 40 K.

in a superlattice

$$\frac{\partial f_\nu(k)}{\partial t} = \frac{e}{\hbar} \mathbf{F} \cdot \nabla f_\nu(k) + \sum_{\nu'} \int \left[ P_{\nu\nu'}(k, k') f_{\nu'}(k') - P_{\nu'\nu}(k', k) f_\nu(k) \right] dk'$$

(1)

where $f_\nu(k)$ is the single-particle distribution function of electrons in a state with wavevector $k$ in subband $\nu$, $P_{\nu\nu'}(k', k)dk'$ is the probability per unit time that a scattering event bringing an electron from a state in band $b$ and wavevector $k$ to a state in band $\nu'$ and wavevector $k'$ occurs, and $\mathbf{F}$ is the external electric field providing the electron drift.

The knowledge of the distribution function then allows us to compute the mean values of all physical observables including the current density across the device.

The various scattering mechanisms affecting the electron dynamics are included into the global probabilities $P_{\nu'\nu}(k', k)$ and may be separated into the following contributions

$$P_{\nu'\nu}(k', k) = P^{opt}_{\nu'\nu}(k', k) + P^{th}_{\nu'\nu}(k', k),$$

(2)

where $P^{opt}_{\nu'\nu}(k', k)$ is the electron-photon interaction part and $P^{th}_{\nu'\nu}(k', k)$ accounts for all thermalization processes.

The aim of the model is to focus on electron-photon interaction thus the latter will be treated in a fully microscopic scheme by use of the Fermi’s golden rule. Conversely, all other interactions will be described in terms of a phenomenological electronic mean-lifetime, $\tau$, guaranteeing the proper thermalization of the electron population in the absence of external electromagnetic fields. Such a mean lifetime therefore enters the model as a fitting parameter, representing the global strength of all non-radiative thermalization mechanisms. A detailed description of the
Figure 2. (Left) Time evolution of the total current (continuous line) at 14K, positive bias and 300K blackbody illumination. Dotted, dashed and dash-dot lines show the current contributions from the first, second and third excited minibands respectively. (Right) Current contribution as a function of electron energy for different temperatures.

The model is quite general and is capable of both stationary and time dependent simulations; in this paper it has been applied to a prototypical superlattice structure with 4nm wells and 12nm barriers with a barrier height of 120 meV. The system exhibits a single miniband below the barrier energy (which we shall call the ground miniband) plus a virtually infinite number of excited minibands at higher energies. Figure 1 shows the total current flowing through the device as a function of temperature, under a 300K blackbody radiation field and a positive applied bias. Since the applied voltage is low enough that the device response is linear, only normalized current values are shown. It can be clearly seen that between 5 and 40K the current output is negative and thus the device exhibits an absolute negative resistance. When temperature is increased over 40K the current starts to grow exponentially due to thermal excitation of carriers from the ground to upper minibands.

This peculiar behaviour can be analyzed in more detail by looking at the time evolution of the total current and to its energetic distribution. The left picture in Fig. 2 shows the current evolution at 14K (continuous line) as well as the contributions coming from the first 3 minibands (dotted, dashed and dash-dot lines). It can be seen that although the stationary value of the total current is negative, a fast sub-picosecond transient is present where the current starts as positive and is then inverted. By looking at the main miniband contributions, coming from the first two excited minibands, it can be seen that this inversion is due to electrons in the first excited miniband carrying a negative current which is bigger, in absolute value, to the current coming from electrons in the second miniband.

On the right of Fig. 2 the same result is shown from a different perspective. The picture shows the relative current contributions from electrons at different energies, for three different device temperatures. It can be seen that current comes from two well separated energy regions corresponding to the first and second excited minibands. Again it can be noted that the first miniband carries a negative current for temperatures below 40K, then the current turns positive as temperature increases. On the other hand, the second miniband is carrying a positive current for every temperature.
This peculiar miniband-specific behaviour can be explained by analytically solving the Boltzmann equation for an N-miniband system interacting with two bosonic thermal baths at different temperatures, namely phonons and temperature $T_0$ and blackbody photons at temperature $T_1$. For space reasons we shall omit the complete calculation and report only the final result. By considering the system evolution at short times it can be shown that a necessary condition for current inversion in a miniband is

$$\frac{\epsilon_\nu}{\epsilon_{\nu-1}} < \frac{T_1}{T_0} - 1$$

where $\epsilon_\nu$ is the width of the $\nu$-th miniband.

This condition shows that there exists a critical device temperature $T_0$ below which the current in a miniband can be negative. For the model structure reported in this paper, the condition is met by the first excited miniband for temperatures below 40K and is never fulfilled by other minibands. Nevertheless since the first excited miniband gives the biggest contribution to the total current, a negative resistance is obtained in any case.

It is important to stress that this effect derives from the joint action of the two thermal baths on the electron population. In fact, in case of absence of one of the two interactions the system would be driven to thermal equilibrium with a temperature equal to $T_0$ or $T_1$ depending on which mechanism is active. The presence of two thermal baths at different temperatures drives the system to a stationary but non-equilibrium state characterized by a distribution function $f_\nu(k)$ exhibiting an inverted convexity with respect to the growth-direction wavevector $k_z$, compared to the equilibrium state. This convexity inversion is what finally determines the current inversion because of the presence of the $\frac{\partial}{\partial k_z}$ term in the drift operator in the Boltzmann equation, which changes sign if the convexity of the distribution function is reversed.

In conclusion, with this study we have shown that absolute negative resistance can be induced in superlattices not only by coherent optical excitation but also by means of a broadband incoherent stimulus like blackbody radiation. Anyway it is necessary to point out that in the simulations presented here, the current coming from the ground miniband has been neglected. This means that from an experimental point of view the observation of this phenomenon could be prevented by the presence of tunneling currents due to ground-state electrons directly crossing the barriers. Anyway, a careful structure design and, possibly, a different choice for the incident broadband field could lead to a measurable effect.

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