Physica B 194–196 (1994) 1333–1334
North-Holland

PHYSICA B

Combined Bloch/SET oscillations in 1D arrays of small tunnel junctions*

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At sufficiently low temperatures, 1D arrays of ultrasmall tunnel junctions with low electron scattering rate (for example, semiconductor superlattices) may exhibit a new type of electron transfer. This process can be considered as fast "Bloch" oscillations with frequency $f_B=\mathcal{E}/h$ (where $\mathcal{E}$ is the electron energy change due to tunneling through one tunnel barrier), modulated with lower "SET" frequency $f_S=I/e$ (where I is the dc electric current through the array).

1. INTRODUCTION

Probably, the most important result of single-electronics (see, e.g., Refs. 1, 2) is the concept [3] of so-called "Single-Electron-Tunneling" (SET) oscillations with frequency $f_S=I/e$, fundamentally related to the dc electric current I. Such oscillations arise due to **particle** properties of electrons and can take place in systems with purely **classical** dynamics [4]. They can be, however, most naturally implemented [5, 6] in 1D arrays of small tunnel junctions.

But it is well known [7] that such systems may allow another type of fundamental oscillations: so-called "Bloch" (or "Stark") oscillations with frequency $f_B=\mathcal{E}/h$, where $\mathcal{E}$ is the free energy change due to electron tunneling through one junction (in the simplest case of negligible self-charging effects, $\mathcal{E}=eEd$, where E is the external electric field and d is the structure period). The Bloch oscillations are evidently a **quantum** phenomenon and reflect **wave** properties of electrons.

A very natural question is whether these two types of oscillations can exist simultaneously. An apparent answer is **no**, because Heisenberg's uncertainty principle forbids the electron to behave simultaneously as a wave and as a particle. The goal of this work was to show that, surprisingly enough, this apparent answer is wrong.

2. MODEL

We have considered a model of 1D structure, typical for description of semiconductor superlattices (see, e.g., Ref. 8). Electron energy in i-th quantum well can be presented as

$$\varepsilon = \varepsilon_0 + eU_i + p^2/2m, \qquad (1)$$

where ε_0 is the 1D energy of the lowest miniband, U_i is the background potential including that due to external electric field, and **p** is the electron momentum in the plane of the well (quantization in this direction is accepted to be negligible). Nonvanishing matrix elements H connect electron states with similar **p** and ε in neighboring layers. On the other hand, **p** can be changed as a result of elastic scattering on impurities, with the rate Γ within the range $H<<\Gamma<<\varepsilon_0$, so that all calculations can be carried out using the perturbation theory with respect to H.

In contrast with the standard approach we, however, considered the superlattice cross-section to be so small and/or temperature T so low that capacitances C and conductances G of all its tunnel junctions satisfy the conditions [1-3] $C<<e^2/k_BT$, $G<<e^2/h$. As a result, single-electron charging effects become important, so that the potentials U_i of wells become dependent on the charge configuration $\{n_j\}$, where n_j is the number of excess electrons in the j-th well. In order to simplify this dependence we have assumed that the number N+1 of the wells is less than $(C/C_0)^{1/2}$, where C_0 is the stray capacitance of the well [5].

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*Supported in part by AFOSR Grant # 91-0445

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SSDI 0921-4526(93)E1247-J

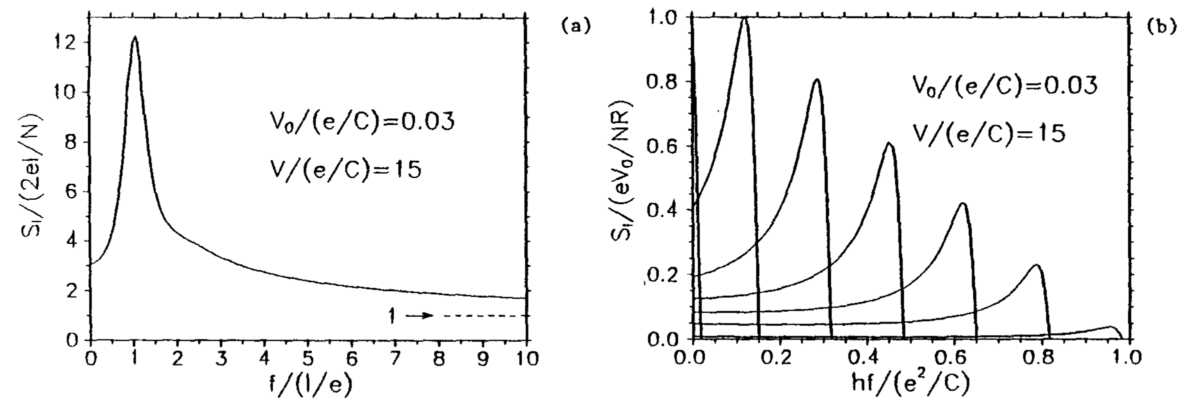

Figure 1. Spectral density of the current I(t) through a "slim" superlattice at (a) low frequencies and (b) high frequencies for 6 of N=30 successive charge configurations (k=1, 5, 10, 15, 20 ,25 ,30). $V_0=\hbar G/e$, T=0.

3. RESULTS

We were able to calculate spectral density $S_I(f)$ of current I(t) through the superlattice (biased by a dc voltage V), for two overlapping frequency ranges: $f \ll f_B$ and $f \gg f_S$. Figure 1a shows a typical result of the calculations for the low-frequency range. One can see a narrow spectral peak corresponding to narrow-band SET oscillations of frequency $f_S=I/e$. These oscillations result from an ordered sequence of single-electron tunneling events [5], so that during each period of the oscillations the system passes through an ordered sequence of successive charge configurations $\{n_j\}_k$ (k=1,...,N) with gradually decreasing energy.

Because of small tunnel barrier transparency, in our model $f_S \ll f_B$. It means that in each of the successive charge configurations $\{n_j\}_k$, the short-time dynamics of the system can be analyzed under the assumption that the configuration is stationary. Figure 1b shows a typical result of such a calculation (with zero-point contribution subtracted, so that the plot shows the available power density). The peak of the density corresponds to the Bloch oscillations of frequency $f_B=\mathcal{E}_k/h$, where $\mathcal{E}_k$ is the energy difference between the charge configurations $\{n_j\}_k$ and $\{n_j\}_{k+1}$. It is important that if $S_I(f)$ is averaged over the period of the SET oscillations, its value at $f \ll f_B$ (equal to 2eI/N) coincides with the low-frequency result in the limit $f \gg f_S$, thus indicating that the picture as a whole is self-consistent.

Thus in "slim" semiconductor superlattices the transport process as a whole can be considered as high-frequency quantum Bloch oscillations modulated by low-frequency classical SET oscillations. The process closely resembles the textbook description of an electron by a packet with wave-like carrier and particle-like envelope. Due to two very different frequency scales (in our case, $f_S \ll f_B$), such a coexistence does not violate Heisenberg's uncertainty relation.

REFERENCES

1. D.V. Averin and K.K. Likharev, in: Mesoscopic Phenomena in Solids, ed. by B. Altshuler *et al.* Elsevier, Amsterdam (1991) 173.
2. H. Grabert and M.H. Devoret (eds.) Single Charge Tunneling, Plenum, New York, 1992.
3. D.V. Averin and K.K. Likharev, J. Low Temp. Phys. 62 (1986) 345.
4. D.V. Averin and K.K. Likharev, in: Nanostructures and Mesoscopic Systems, ed. by W. Kirk and M. Reed, Acad. Press, Boston (1992) 283.
5. K.K. Likharev, N.S. Bakhvalov, G.S. Kazacha, and S.I. Serdyukova, IEEE Trans. Magn. 25 (1989) 1436.
6. P. Delsing, K.K. Likharev, L.S. Kuzmin, and T. Claeson, Phys. Rev. Lett. 63 (1989) 1861.
7. L. Esaki and R. Tsu, IBM J. Rev. Devel. 4 (1970) 61.
8. E.S. Borovitskaya and V.M. Genkin, Solid State Commun. 46 (1983) 769.