THE INTERFERENCE EFFECTS IN THE SLIDING CHARGE DENSITY WAVE

D. Jelčić*, A. Bjeliš** and I. Batistić**
* Department of Physics, Faculty of Science, POB 166, 41001 Zagreb, Yugoslavia
** Institute of Physics of the University, POB 304, 41001 Zagreb, Yugoslavia

Abstract

The dynamics of the charge density wave (CDW) in the external dc-ac electric field is analysed within the Gor'kov model. The interference effects, manifested as finite steps in voltage vs dc field, are present at all rational ratios of the external ac frequency and the intrinsic frequency of the coherent oscillations, in agreement with the experimental results. It is also shown that the beats in the voltage are to be expected in the vicinity of resonances.

The coherent voltage oscillations in highly anisotropic materials like tri- and tetra-halcogenids, blue bronzes and some organic compounds, are nowadays considered as a general property of the collective transport by the charge density wave (CDW). Frequency spectra of these oscillations, refered often as a narrow band noise (NBN), have a multiharmonic content with a single or few fundamental frequencies ω_{int} proportional to the CDW current /1/.

The sample response to simultanuous ac and dc external fields (i.e. currents) shows the interference effects between these oscillations and the ac field. The interferences are manifested as finite steps in dc current-voltage curves V(I), resulting from the phase locking of the CDW current onto the ac drive. Such steps, named the Shapiro steps by analogy to similar effects in ac-dc driven Josephson junction, are found /1,2/ at all the harmonic ratios of ω_{int} and the external frequency ω_{ext}, $n\,\omega_{int} = m\,\omega_{ext}$, where n and m are integers.

In spite of numerous studies of the NBN and Shapiro steps, the mechanism responsible for both the phenomena is still a matter of controversies /3/. The main question is whether they are bulk or local effects. Some indications /4/ are in favor of the idea that they are generated in the regions where the CDW velocity undergoes sharp discontinuities. An example of such regions are ohmic contacts imposed on the sample. Due either to mechanical strains or to a local decrease of the electric field, the contacts can strongly deform the CDW or even stop its translation, enforcing the CDW current to convert into the ohmic one. One possible way of performing this conversion are the fast localized collapses of the CDW amplitude near the contacts, during which the CDW phase slips for ± 2 π. These time dependent local deformations of the CDW induce beats in the sample voltage that may account for the NBN. In this article we show that the corresponding effects in the ac external electric field lead to the interference (Shapiro) steps.

We start from a microscopic model developed by Gor'kov /5/, in which the CDW dynamics is described by the equation of motion

$$\partial_t \Delta + iE\,\Delta - \partial_x^{\,2}\,\Delta - \partial^2\,\Delta - \Delta + |\Delta|^2\,\Delta = 0, \tag{1}$$

while the associated voltage is given by

$$V_{PS} = \lambda \int dx\,[\,|\Delta|^2\,E - \epsilon\,|\Delta|^2\,\partial_t \phi\,]. \tag{2}$$

Here $\Delta = |\Delta| \exp(i\phi)$ is a dimensionless order parameter which determines the local lattice distorsion (i.e. the corresponding electronic charge density) in terms of its thermodynamic value in the Peierls state, $|\Delta_\infty|^2 = (6/5)\,\pi^2\delta^2$ with $\delta^2 = T_p^{\,2}\,(1 - T^2/T_p^{\,2})$. T_p is the Peierls transition temperature, strongly suppressed with respect to the critical temperature of clean samples ($T_p < T_p^{\,0}$) due to high concentrations of weak impurities in the bulk of the specimen. The electric field E, time t and the longitudinal coordinate x in the equations (1) and (2) are dimensionless and are measured in terms of $\pi^2\delta^2/6\,\bar{v}_x e$, $\omega_o^{-1} = (16\pi\gamma\delta^2/27T_p^{0\,2})^{-1}$ and the longitudinal correlational length $\xi_{\prime\prime}^2 \sim v_x^{\,2}/\delta^2$, respectively. $\bar{v}_x$ is the mean longitudinal electronic velocity, and γ is the Euler constant. In the equation (2) $\epsilon = \frac{8}{9}\,\bar{v}_x^{\,2}/\bar{v}_x^{\,2} \sim 1$ and $\lambda \sim \delta^2/T_p^{0\,2} << 1$. The transverse correlations will not be considered here.

A simple translational solution of the equation (1), $\Delta = \exp(-iEt)$ corresponds to the rigid CDW which slides under the influence of an external electric field. However, when boundary conditions of fixed amplitude Δ and phase ϕ at the contacts ($\Delta(x_{cont}, t) = 0$) are superimposed, the equation (1) leads to the appearence of the phase-slippages at distances x_{PS} ($x_{PS} >> \xi_{\prime\prime}$) from the contacts positions /5,7/. For dc driving fields the PS's are shown numerically /6/ to repeat periodically in time with the frequency proportional to the uniform CDW current in the sample interior. A contribution to the sample voltage (2) coming from the PS region then consists of sharp (nonsinusoidal) pulses with the fundamental frequency ω_{int} equal to the rate of the PS's.

Here we present the numerical analysis of the equation (1) with the electric field $E(t) = E + E_1 \cos(\omega_{ext}\,t + \phi_o)$ and show that the multiharmonic content of the intrinsic PS pulses leads to the unusual interference effects. These interferences appear to be a consequence of nonlinear mixing of the two frequencies, ω_{int} and ω_{ext}. Their interplay is directly evident in the frequency spectrum of the induced PS voltage, depicted in Fig. 1 for the external frequency that is close to the intrinsic PS frequency. The latter is equal to the dc field E in our dimensionless notation. Positions of discrete peaks are identified as the modulation frequencies $\omega_{nm} = |n\omega_{int} - m\omega_{ext}|$, where m, n = 0, ± 1, ± 2...

We emphasize particularly the low frequency peaks at $\omega_{11} = |\omega_{int} - \omega_{ext}|$ and its higher harmonics ω_{nn}, $n > 1$. They correspond to the multiharmonic modulation of the PS voltage in a time interval of the common periodicity of the ac field and the PS's. Fig. 2 shows this modulation on the direct time scale, for two symmetric values of dc fields close to a resonant value, $\omega_{int} = \omega_{ext} \pm |\delta\,\omega|$. Its multiharmonicity comes from the tendency of the phase-slippages to lock their rate onto the external ac periodicity.

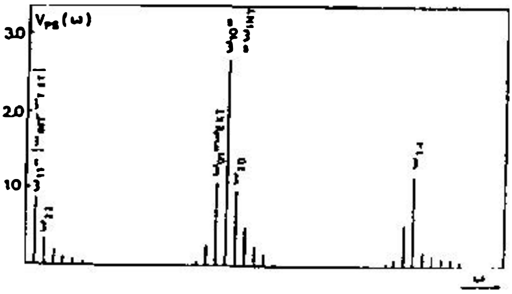

Fig. 1. The Fourier spectrum of the PS voltage near the fundamental resonance ($\omega_{int} = 0.500$, $\omega_{ext} = 0.525$, $E_1 = 0.30$)

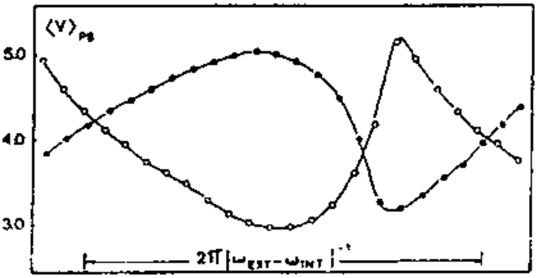

Fig. 2. The sample voltage averaged over each successive PS period, $<V>_{PS}$ vs time, for $E_1 = 0.30$, $\omega_{ext} = 0.500$ and ω_{int} equal to 0.525(●) and to 0.475(o)

Yet, a total CDW phase accumulated at the contacts throughout the period of the modulation is defined by the uniform current in a sample interior, i.e. by the dc field. Compensation due to the continuity requirement, is performed in short time intervals in which the time between two successive PS's is significantly shortened (for $\omega_{int} > \omega_{ext}$) or prolonged (for $\omega_{int} < \omega_{ext}$) with respect to $2\pi/\omega_{ext}$ (Fig. 3). The breaking of the phase coherence between the PS's and the ac field results in the beats in the sample voltage, that vanish only in the resonance. As shown in figure 2. these beats are qualitatively different when the system is reaching or surpassing the ac periodicity, i.e. for different signs

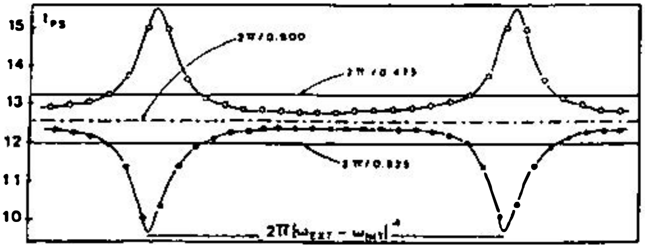

Fig. 3. Time intervals between the successive PS's before and after the resonance. Parameters are the same as in Fig. 2.

of $(\omega_{ext} - \omega_{int})$. This dependence leads to finite step in dependence of the sample voltage (averaged over the period of modulation) on the dc field. As is evident from Fig. 4., by increasing the ratio E_1/E this effect becomes more and more prominent.

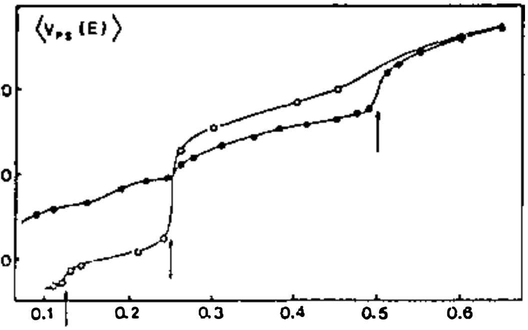

Fig. 4. Time averaged PS voltage vs external dc field for $E_1 = 0.30$ and $\omega_{ext} = 0.5$ (●) and 0.25 (o). The resonant steps correspond to the harmonic ratios of ω_{int} and ω_{ext}.

Passing through the other harmonic ratios of ω_{int} and ω_{ext}, $\omega_{int}/\omega_{ext} = m/n \neq 1$ similar effects are also found and lead to higher order resonant steps. However, as m and/or n increase, the amplitudes of the voltage modulations, and in particular differences between two sides of the resonances, become less significant. The corresponding harmonic and subharmonic Shapiro steps become soon too weak to be distinguished numerically, as well as experimentally /1–3/. The additional dependence of the steps heights on E_1 and E are under current investigations.

In conclusion, the numerical solutions of the equation (1) for time dependent electric field show, in agreement with an earlier analytical study /7/, that the Gor'kov model accounts for the interference effects observed experimentally in the CDW compounds like $NbSe_3$ and TaS_3/3/. In addition to finite harmonic and subharmonic steps, we have also found highly nonsinusoidal low frequency modulations of the voltage by approaching the resonant values of $\omega_{int}/\omega_{ext}$. The experimental investigations in the vicinity of resonances, that would detect this effect, are highly desirable.

REFERENCES

1. P. Monceau, J. Richard and M. Renard, Phys. Rev. Lett. **B25** (1982), 931.
   J. Richard, P. Monceau and M. Renard, ibid, p. 948.
2. S. E. Brown, G. Mozurkewich and G. Grüner, Phys. Rev. Lett. **52** (1984), 2277.
   M. F. Hundley and A. Zettl, Phys. Rev. **B33** (1986), 2883.
3. For a recent review on CDW dynamics see e.g. G. Grüner and A. Zettl, Physics Reports **119** (1985), 117.
4. N. P. Ong and G. Verma, Phys. Rev. **B27** (1983), 4495.
   T. W. Jing and N. P. Ong, Phys. Rev. **B33** (1986), 5841.
   R. P. Hall, M. E. Hundley and A. Zettl, Phys. Rev. Lett. **56** (1986), 2399.
5. L. P. Gor'kov, Zh. Eksp. Teor. Fiz. 86 (1984), 1818. (Sov. Phys. JETP 59 (1984), 1057)
6. I. Batistić, A. Bjeliš and L. P. Gor'kov, J. Physique **45** (1984), 1049.
7. A. Bjeliš and D. Jelčić, J. Physique Lett. **46** (1985), 283.