Response to a weak microwave radiation from a quasi-one-dimensional conductor $NbSe_3$ with microwave pumping

I. B. Bendik, A. N. Ermolenko, and V. M. Pchelkin
V. I. Ul'yanov (Lenin) Electrotechnical Institute, Leningrad

(Submitted 14 April 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 12, 622–624 (25 June 1988)

$NbSe_3$ crystals were studied experimentally at $T < 59$ K under the action of a weak microwave signal with a frequency ω_s. This study was carried out with the stipulation that the crystal be placed in a static electric field and a microwave pump field of strengths E_0 and E_{pump}, causing a depinning of the charge density wave. A response to the microwave radiation of less than 0.1 μW power level was obtained at a microwave pump power level on the order of 10 μW.

Crystals of $NbSe_3$, a quasi-one-dimensional conductor, in the dielectric state are known to exhibit nonlinear electric properties which can be explained in terms of the effect of the charge density wave on the transport processes. A charge density wave is set in motion in a constant electric field whose strength E_0 exceeds the threshold value E_{thr}. At $E_0 = E_{\text{thr}}$ the charge density wave becomes depinned. A simultaneous action of static and rf fields causes the threshold field to change. The strength of E_{thr} in this case depends on the amplitude of the pump field.[1-3] Latyshev *et al.*[3] showed that below the temperature of the second transition ($T_{p2} = 59$ K) the threshold field of $NbSe_3$ samples changes as a result of application of a microwave pump field and that the pump field synchronizes the normal modes of the charge density wave up to a frequency of 3 GHz.[4] We have attempted to detect a charge-density-wave response to a weak microwave excitation at $E_0 > E_{\text{thr}}$ by directly detecting and recording a rectified current. We have not been able, however, to obtain positive results. Since it has been shown experimentally[3,4] that the action of a microwave pump field markedly perturbs the charge density wave, we can assume, nonetheless, that a response to a weak microwave radiation can be detected if a strong pump field will act simultaneously with this microwave radiation on the charge density wave. In this letter we describe such an experiment.

A $NbSe_3$ crystal is placed in a static field and a microwave field with a frequency ω_{pump}. The strength of the bias field and the amplitude of the pump field E_{pump} are chosen in such a way that there would be a depinning ($E_0 + E_{\text{pump}} > E_{\text{thr}}$). This system is excited by a weak microwave signal with an amplitude $E_s \ll E_0$, E_{pump} and with a frequency ω_s, which is close to the frequency ω_{pump}, so that $\omega_s - \omega_{\text{pump}} = \Omega$ and $\Omega \ll \omega_s$, ω_{pump}. As the response to the microwave signal we measured the alternating voltage of the samples which varied with a frequency Ω in accordance with the harmonic law.

As experimental samples we used crystals with transverse linear dimension of 3–7 μm. The crystal was mounted on the surface of a polished aluminum-oxide ceramic substrate between the gold contact surfaces which were produced photolithographically. A layer of indium, which established mechanical and electrical contacts, was deposited on the surface of the crystal and on the contact surfaces. During the deposition of indium, we used a shadow stencil to protect a part of the crystal surface from indium deposition. The remaining indium-free part of the crystal between the contacts is the effective region of length 30–200 μm. In the temperature interval 20–35 K the direct-current resistance of the samples is 7–50 Ω. The threshold voltage of the various samples is 2–16 mV in the indicated temperature interval.

To achieve microwave matching and to make it possible to connect a bias circuit and an output circuit, we included on this substrate coincidence circuits and filters in the form of an integrated circuit on microstrip lines. Drawing upon the experience gained from the research and development of integrated microwave circuits[5] we calculated the microwave voltage and chose the required operating conditions.

The microwave radiation from the pump generator and the weak-signal generator was fed to the integrated circuit through a coaxial cable and a coaxial-strip junction. The substrate with the integrated circuit was mounted on a substrate support in which a temperature sensor was embedded.

The experiments were carried out in the transportable helium container of the Dewar. As the pump generator and the signal generator we used standard measuring microwave generators. The signal generator operated either in the fixed mode ω_s or the oscillating mode. To identify the response signal of the difference frequency, we used a CK4-59 spectrum analyzer with a frequency scanning range of 0.5–100 MHz. The constant-bias source was based on the current generator circuit. The response signal was measured directly from the $NbSe_3$ sample. Tests were carried out with twelve samples. The results were found to be easily reproducible.

Figures 1 and 2 show the results of the experiment carried out at the pump generator frequency of 3.3 GHz at $T = 28$ K. The variable parameters are the bias voltage, pump power level, and the signal power level. Figure 1 is a plot of the amplitude of the response with a frequency $\Omega/2\pi = 36$ MHz as a function of the bias voltage at fixed microwave signal power levels for sample 10. The threshold voltage in

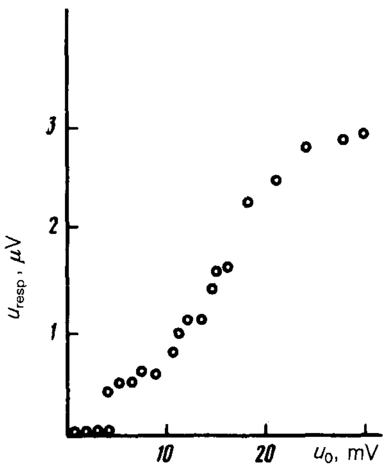

FIG. 1. Amplitude of the response voltage vs the bias voltage. $P_{pump} = 100$ μW, $P_s = 0.1$ mW.

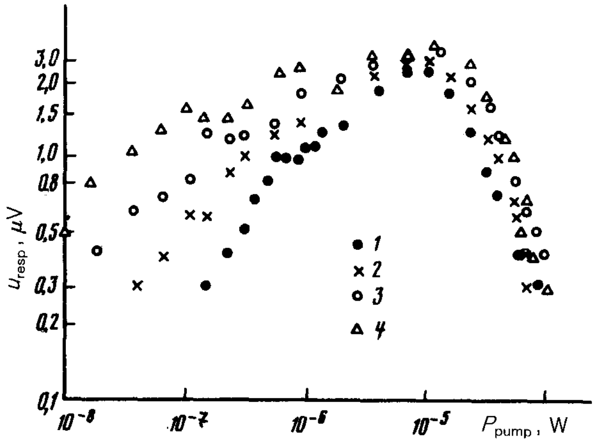

FIG. 2. Amplitude of the response voltage vs the microwave pump power level for various bias voltages μ_0, in mV: 1—10; 2—12; 3—14; 4—16.

the absence of the microwave signal is $u_{thr} = 7$ mV, consistent with the field strength $E_{thr} = 0.35$ V/cm. The resistance of the sample is 40 Ω. The amplitude of the microwave pump voltage is commensurable with the constant bias voltage and at $P_{pump} = 10\ \mu$W is ~30 mV.

Figure 2 is a plot of the amplitude of the response versus the microwave pump voltage for various values of the bias voltage and for a fixed microwave signal power level. The response depends linearly on the signal voltage if the condition $P_s \ll P_{pump}$ is satisfied. The signal power level was found to be $< 1\ \mu$W in all the measurements. A change in the generator signal frequency on switching to the frequency oscillation mode showed that the response does not depend on the difference frequency Ω at the tested microwave pump and signal power levels, as indicated by the spectrum analyzer frequency band.

The results which we have obtained show that the charge density waves are highly sensitive to the action of a weak microwave signal in the case of a depinning caused by the joint action of the fixed bias voltage and microwave pumping.

We wish to thank Ya. S. Savitskaya and Yu. I. Latyshev for interest in this study and for furnishing $NbSe_3$ crystals. We also thank D. N. Balyasov for participation in the experiment.

[1]A. Zettl and G. Grüner, Phys. Rev. **B25**, 2081 (1982).
[2]I. B. Bendik, Pis'ma Zh. Tekh. Fiz. **10**, 784 (1984) [Sov. Tech. Phys. Lett. **10**, 329 (1984)].
[3]Yu. I. Latyshev, V. E. Minakova, and Yu. A. Rzhanov, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 31 (1987) [JETP Lett. **46**, (1987)].
[4]Yu. I. Latyshev and V. E. Minakova, in: Nonuniform Electron States, Proceedings of the Second All-Union Symposium, Novosibirsk, **21**, 1987, p. 16.
[5]G. S. Khizha, I. B. Bendik, and E. A. Serebryakova, Microwave Phase Shifters and Switches, Radio and Communications, Moscow, 1984, p. 184.

Translated by S. J. Amoretty