Depinning of the Charge-Density Wave in $NbSe_3$

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Abstract

In the non-Ohmic regime of $NbSe_3$, an evidence that the charge-density wave (CDW) slides as a whole over the whole crystal is obtained by investigating both the transient conductivity under pulsed field and the periodic noise. It is also confirmed that the configuration of the CDW changes as it begins to slide.

In both the incommensurate q_1- and q_2-CDW states of $NbSe_3$, the CDW begins to slide when an applied electric field exceeds a well defined threshold E_T and its sliding gives rise to the large extra conductivity[1,2]. The extra conductivity is highly anisotropic; the CDW can slide only along the direction parallel to the nesting vector[3,4]. The damping of the sliding CDW is due to impurity scattering even in a pure crystal with residual resistance ratio larger than 100.[5] However, details of CDW sliding are not sufficiently clarified. One of important problems left unclarified is whether the CDW slides as a whole on a macroscopic scale. Various phenomena, which are expected to give a clue to clarify such a problem, have been found in the non-Ohmic regime above E_T. Phenomena subjected to extensive investigations are the transient conductivity under pulsed field[6,7] and an appearance of narrow band noises.[2,8]

The extra conductivity increases gradually on a time scale of 100 μsec after turning on pulsed field and attains to a steady value. Metastable states of the CDW are formed in sliding of the CDW[6]. These facts suggest that the configuration of the CDW changes on a macroscopic scale as the CDW begins to slide. The narrow band noise is coherent over many periods and its frequency is proportional to the CDW current[9]. A simple explanation of the narrow band noise is that the drift velocity of the CDW is modified by the impurity potentials periodically as it slides as a whole over a finite range[9]. Another explanation, proposed recently, is that the narrow band noise is caused by phase vortices which generate locally around the electrical contacts for measuring the conductivity[10].

In this work, the non-linear resistance R_E of the several crystals including one which exhibits the narrow band noise with only one fundamental frequency was measured under pulsed field with various waveforms. The periodic noise superposed on R_E was compared with the noise spectrum measured under dc bias. From both the transient behavior of R_E under pulsed-field with two steps and the nature of the periodic noise, it was found, in a crystal of high quality, that the CDW slides as a whole over the whole crystal.

To measure resistance, constant pulsed voltage was applied to a series of the sample and a standard resistor R_s. Both the sample voltage and the current voltage appearing in R_s were amplified by a differential amplifier with a bandwidth of 15 MHz and followed to channels A and B of a digital boxcar integrator. Resistance was calculated by operating A/B mode of the boxcar integrator. The results were fed to a X-Y recoder. The rise and recovery times of both sample and current voltages were less than 0.2 μsec. Pulse-width was in the range 0.5 μsec - 1.5 msec with repetition times of 5 - 50 msec. A four probe method was used for pulsed experiments. Lead wires were attached to a crystal with silver paint. In measurements of the noise spectrum under dc bias, sample voltage was amplified by the same differential amplifier used in pulsed measurements and fed to a spectrum analyzer. Temperature was stabilized within ±30 mK during the course of a measurement. Resistance under single shot pulsed field was also investigated by measuring the sample voltage with constant current. The sample voltage was displayed on a storage scope. A sample was cooled down from the transition temperature without the application of electric field, and then the first pulse was applied to the sample. Second, third and forth pulses in the same direction to the first were applied every several tens of seconds after turning off the preceding pulse.

Voltage response to single shot pulse is shown in Fig. 1. Although the sample voltages decrease gradually to the same steady value, the transient time to the steady state is rather short under the first pulse in comparison with that under the second. Transient decreases of sample voltages under second, third and forth pulsed fields are the same to each other. These facts indicate that the CDW is left in a metastable state after the CDW ceases its sliding.

In Fig.2, resistance measured under repeated pulsed field is shown together with the sample and the current voltage. The resistance decreases gradually from the Ohmic value to the steady one on a time scale of 100 μsec. Above the second threshold field, denoted by E_{T2} hereafter, the resistance drops instantaneously to a value smaller than the Ohmic value and then decreases gradually to the steady one. These behaviors are in accordance with those reported previously[6]. The steady values, which are measured 500 μsec after turning on pulsed field, are plotted as a function of field strength in Fig.3. Its field dependence is described by tunneling theory[11] as well as the dc data.

Resistance measured under two successive pulsed fields are shown in Fig.4. When the duration time T_d between the first and the second pulses is sufficiently long, larger than 500 μsec, the same transient decrease of R_E is observed under the first and the second pulsed field (Fig.4(a)). As T_d is made shorter, the transient behavior under the field of the second pulse becomes less distinct (Fig.4(b)). Finally, when T_d is made shorter than 10 μsec, resistance under the second pulse does not show the transient behavior and attains instantaneously to the same steady value with that under the first (Fig.4(c)). These results mean: the configuration of the CDW is different between the CDW being in sliding and one at rest. the former configuration remains unchanged within several μsec after turning off pulsed field though the CDW is at rest, and relaxes to a metastable one within several tens of μseconds. The CDW with the former configuration does not show the transient behavior after turning on pulsed field while one with the latter configuration does.

In Fig.5A, resistance measured under pulsed-field with two steps is shown for three different heights of the second step. The first stepped field is slightly larger than E_T. When R_E attains to the steady value completely under the first stepped field, the field is stepped up. The resistance drops instantaneously to the steady value at this second step, as seen in Fig.5A. If the field dependence of $\Delta\sigma_E$ is due to the existence of many domains with different E_T, some domains would slide under the first stepped field and other domain would begin to slide when the field is stepped up to the second one. In other words, the number of carriers rather than their mobility would increase as the field is increased. On the other hand, when the single pulsed field whose amplitude is equal to the second field of two stepped pulse is applied, the resistance decreases gradually from the Ohmic value to the steady value as far as the field is limited below E_{T2}, as shown in Fig.5B(a),(b). The steady value is the same with that measured under the second field of two stepped pulse. This fact means that sliding of any domain which is able to slide below E_{T2} would give rise to the gradual decrease of resistance. Then, in the measurement under pulsed-field with two steps, the resistance must decrease gradually to the steady value under the second stepped field as well as under the first. However, present results are not the case, as seen in Fig.5A(a),(b). This means that the number of carriers causing the extra conductivity is constant and the field dependence of $\Delta\sigma_E$ is due to that of their mobility below E_{T2}. The field dependence of $\Delta\sigma_E$ above E_{T2} can be also considered due to mobility as well as below E_{T2} from followings. First, the resistance drops instantaneously to the steady value also when the field is stepped up to the second one which is larger than E_{T2} (Fig.5A(c)). Second, the extra conductivity $\Delta\sigma_E$ of the steady state would be enhanced if new domains are depinned at some field, but such an enhancement of $\Delta\sigma_E$ is not observed at E_{T2} in the $\Delta\sigma_E$ - E curve. It is therefore concluded from these results that the CDW is depinned as a whole over the whole crystal at E_T.

The result measured in higher resolution of the time is shown in Fig.6. The crystal is the same on which data shown in Fig.5 were taken. An interesting feature is that the resistance remains its Ohmic value for a short time after turning on pulsed field. The initial persistency of the Ohmic value becomes shorter with increasing field strength. When the field larger than E_{T2} is applied, this persistency cannot be observed and resistance drops instantaneously to a value smaller than the Ohmic one. Another feature is that the large periodic noise is observed just after the resistance begins to decrease and its amplitude decreases gradually with the lapse of the time. A large periodic noise can be observed only in the crystal which exhibits the narrow band noise with only one fundamental frequency in the noise spectrum. Figure 7 shows the noise spectrum of the crystal on which both data shown in Fig.5 and 6 were taken. The noise spectrum was measured by using two probe method. It should be noted that the narrow band noise with only one fundamental frequency and no enhancement of the broad band noise are observed at least up to 4 E_T in the present crystal.

In the pulsed measurement, the frequency of the periodic noise increases as the resistance decreases after turning on pulsed field i.e. as the CDW current increases. However, being normalized by the CDW current I_C, the noise frequency measured just after turning on pulsed field is the same with that in the steady state which is measured by a spectrum analyzer, as shown in the Table. The normalized frequency is invariant after turning on pulsed field.

Table : Noise frequency normalized by the CDW current I_C for three values of the electric field E. ν^i (I_C^i) and ν^{dc} (I_C^{dc}) are frequency (CDW current) measured just after turning on pulsed field and one measured in the steady state respectively.

E (mV/cm)	ν^i (MHz)	ν^{dc} (MHz)	ν^i/I_C^i (MHz/μA)	ν^{dc}/I_C^{dc} (MHz/μA)
61.0	2.5	4.0	0.43	0.44
72.2	6.1	7.2	0.47	0.48
79.6	6.9	8.2	0.44	0.46

The noise frequency measured under dc bias (Fig.7) is proportional to the nonlinear current $I_C(=en_cv_C)$ due to CDW sliding. The number of carriers n_c in the steady state is found field independent from the experiment on pulsed-field with two steps. It is therefore concluded that the noise frequency ν is proportional to the drift velocity v_C of the CDW. Then, ν/I_C can be written as

$$\nu/I_C = \nu/en_c v_C \propto 1/n_c ,$$

where e is the electronic charge. The invariance of the normalized frequency means that n_c is time independent, that is, the CDW begins to slide as a whole after turning on pulsed field. The transient decrease of resistance under pulsed field is due to the increase of v_C. Together with the result obtained from the experiment on pulsed-field with two steps, this result concludes that the CDW slides coherently over the whole crystal. This conclusion is consistent with the fact that only one fundamental noise frequency is observed in this crystal.

To discuss the phenomena mentioned above, we assume that both weak and strong pinning sites are distributed in the crystal. The number of the latter sites will be very small. The phase of the CDW deforms spatially to gain the potential energy at pinning sites. Especially the maxima (or minima) of the CDW will be positioned on strong pinning sites. When the field above E_T is applied, the CDW begins to slide at first except the neighborhood of the strong pinning sites. Compression and expansion occur on the back and front sides of the strong pinning site respectively, because the phase of the CDW is still pinned at these sites. Such a deformation costs strain energy still more. As the CDW between the strong pinning sites continues to slide, strain energy overcomes the strong pinning potential at last and depinning occurs. Resistance will remain in its Ohmic value until the first depinning occurs at the strong pinning site, as seen in Fig.6. As the applied electric field is increased above E_{T2}, the field energy which is gained when the CDW slides, by one wavelength, as a whole but over a finite volume will be sufficient to overcome the strong pinning potential. The CDW can begin to slide without the initial deformation. Then no initial persistency of the Ohmic value will appear. On the other hand, the amplitude of the periodic noise damps with the lapse of the time, as seen in Fig.6. This result suggests that the phase of the sliding CDW becomes uniform gradually as the CDW continues to slide. In the steady state the phase of the CDW is rather uniform over a crystal. A uniform phase of the sliding CDW reduces the effective pinning potential and then the modification of the drift velocity which is expected to cause the periodic noise becomes small. According to reduction of the effective pinning potential, the drift velocity will increase as expected from the experimental result that the crystal with smaller value of E_T, namely, weaker pinning potential exhibits larger extra conductivity under fixed field strength.

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Figure captions

Fig. 1: Transient decrease of resistance under single shot pulsed field. The lower and the upper curves are the first and the second pulsed field respectively.

Fig. 2: Transient decrease of resistance under pulsed field. Waveforms of the sample and the current voltages are also shown.

Fig. 3: Field dependence of the extra conductivity measured by dc and pulsed method. In the latter method, the conductivity was measured 0.2 μsec, 0.5 μsec and 500 μsec after turning on pulsed field. The arrow indicates E_{T2} of this crystal.

Fig. 4: Transient decrease of resistance under two successive pulses. Duration time between two pulses is (a) 660 μsec,(b) 120 μsec,(c) 10 μsec.

Fig. 5: Resistance measured under (A) pulsed-field with two steps and (B) single pulsed field of the same strength with the second of (A).

Fig. 6: Resistance measured in higher resolution of the time. The crystal is the same on which data shown in Fig.5 were taken. The periodic noise damps with the electric field above E_{T2}. The arrow indicates the period of the initial persistency.

Fig. 7: Noise spectrum under dc bias. The crystal is the same on which both data shown in Fig.5 and 6 were taken.

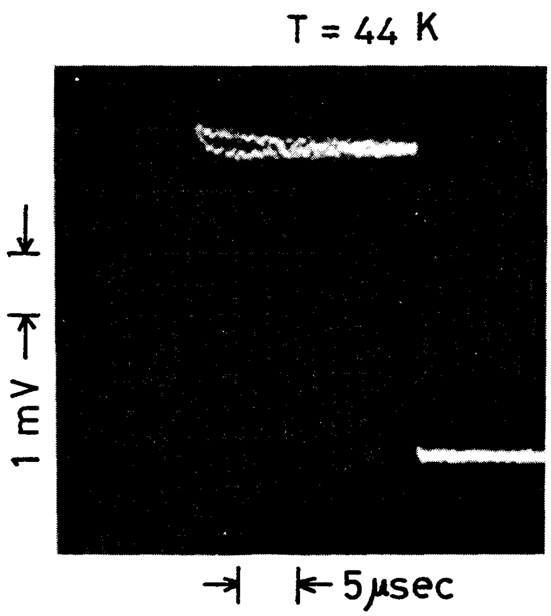


Fig. 1

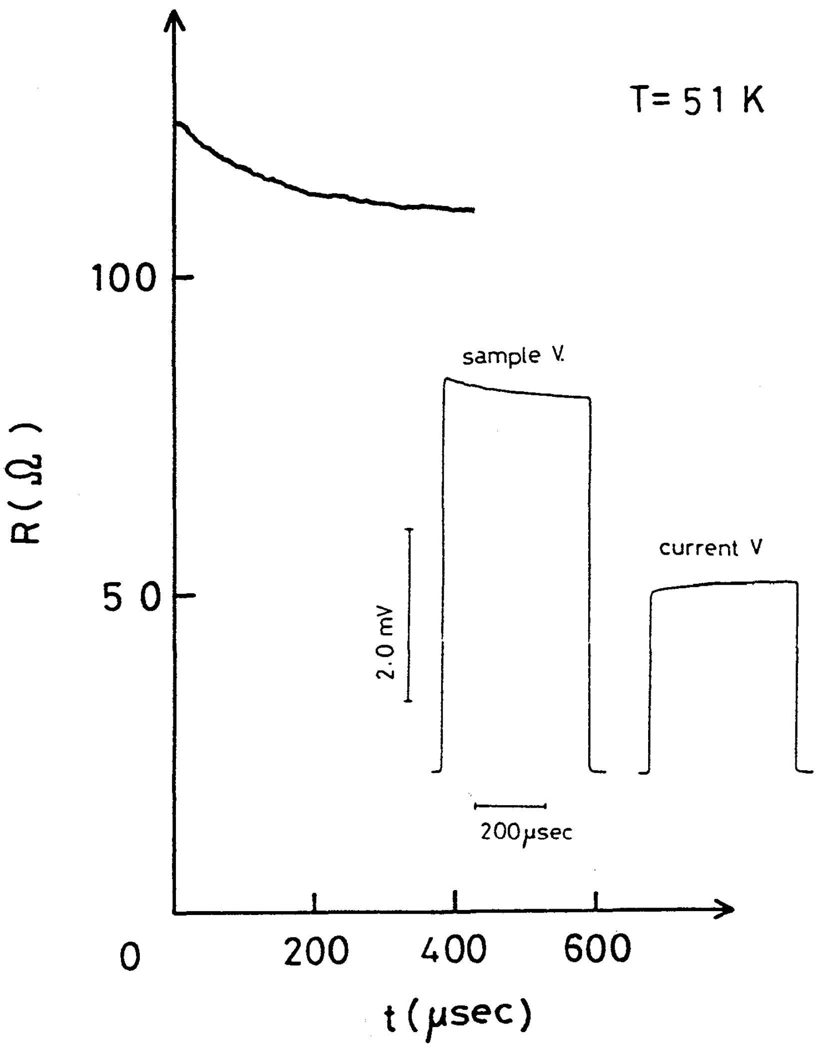
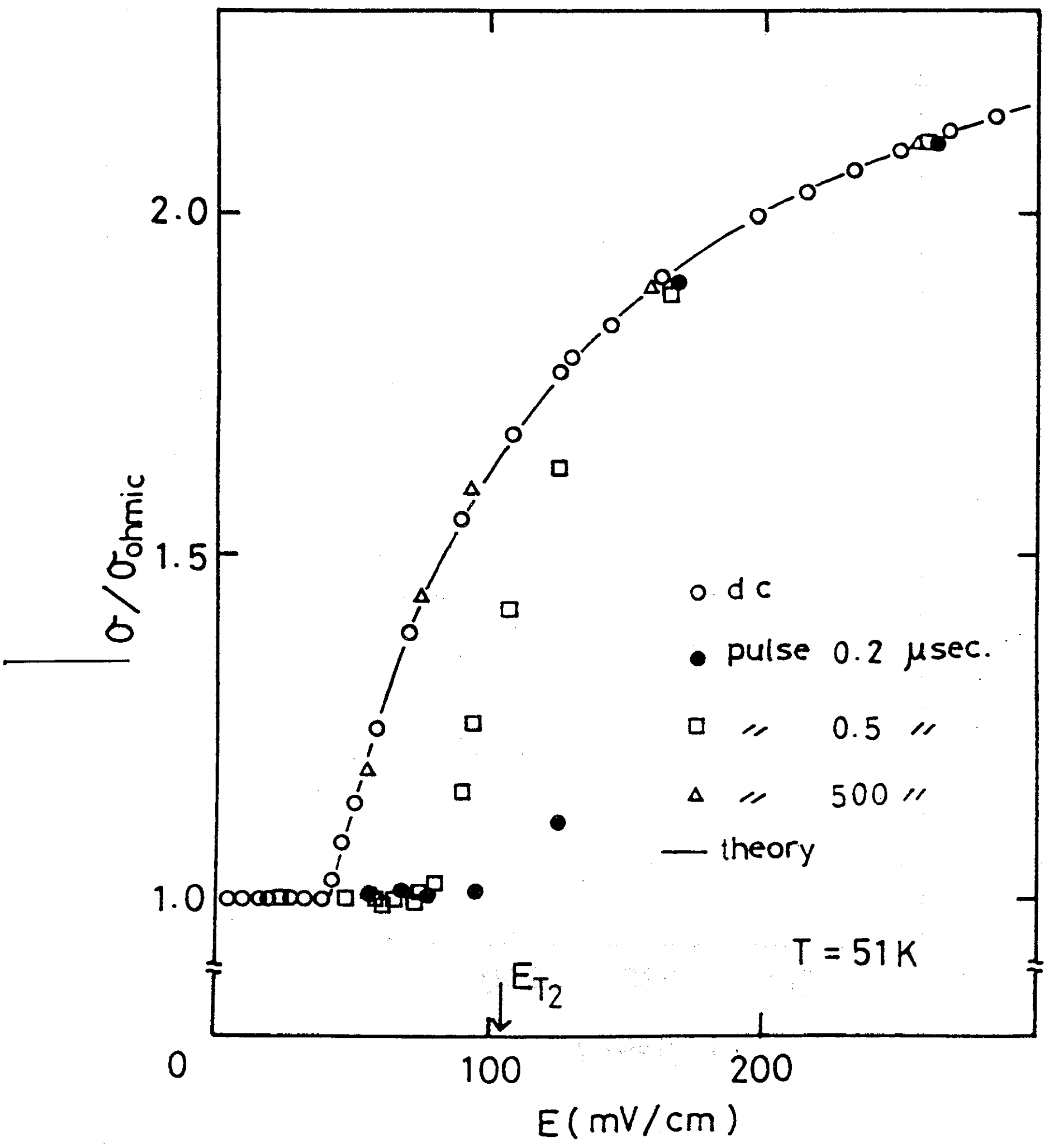

T= 51 K
100
R (Ω)
5 0
sample V.
2.0 mV
current V
200μsec
0
200
400
600
t (μsec)

Fig. 2



2.0
1.5
1.0
σ/σ_ohmic
o d c
● pulse 0.2 μsec.
□ 〃 0.5 〃
△ 〃 500 〃
— theory
T = 51 K
E_T2
0
100
200
E(mV/cm)

Fig. 3

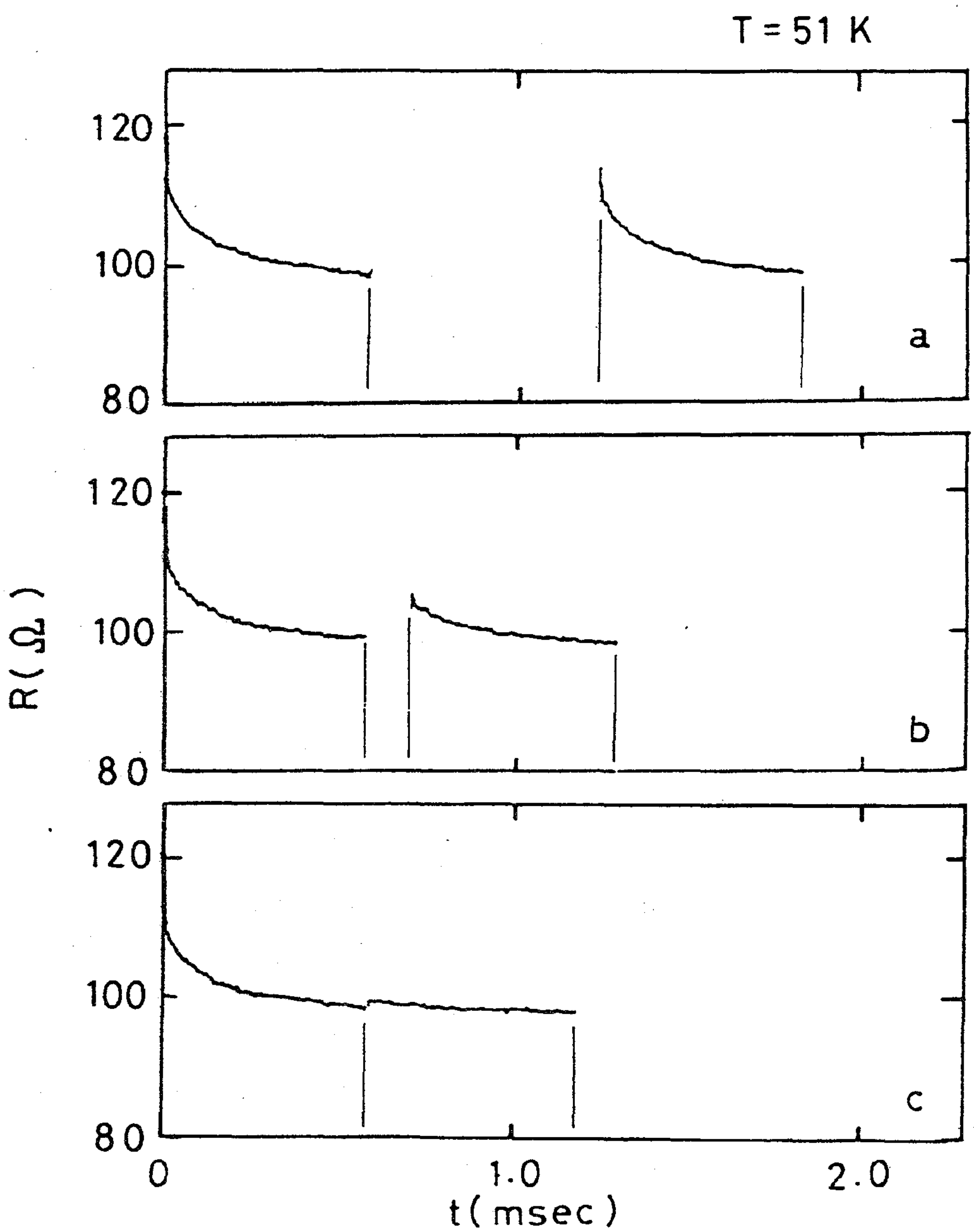


Fig. 4

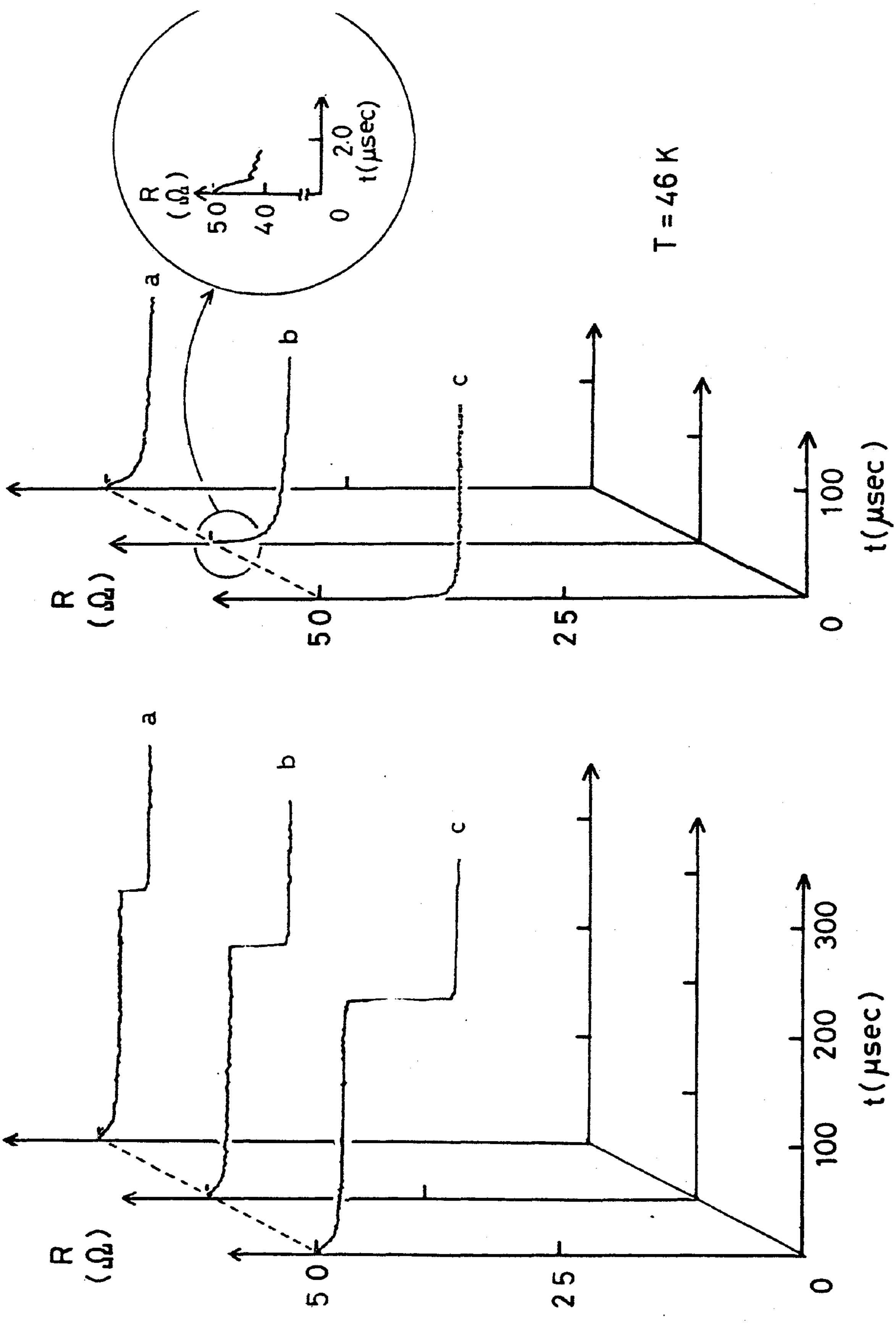

R (Ω)
50
25
0
100
200
300
t(μsec)
(A)
a
b
c
R (Ω)
50
25
0
100
t(μsec)
(B)
a
b
c
R (Ω)
50
40
0
2.0
t(μsec)
T = 46 K

Fig. 5

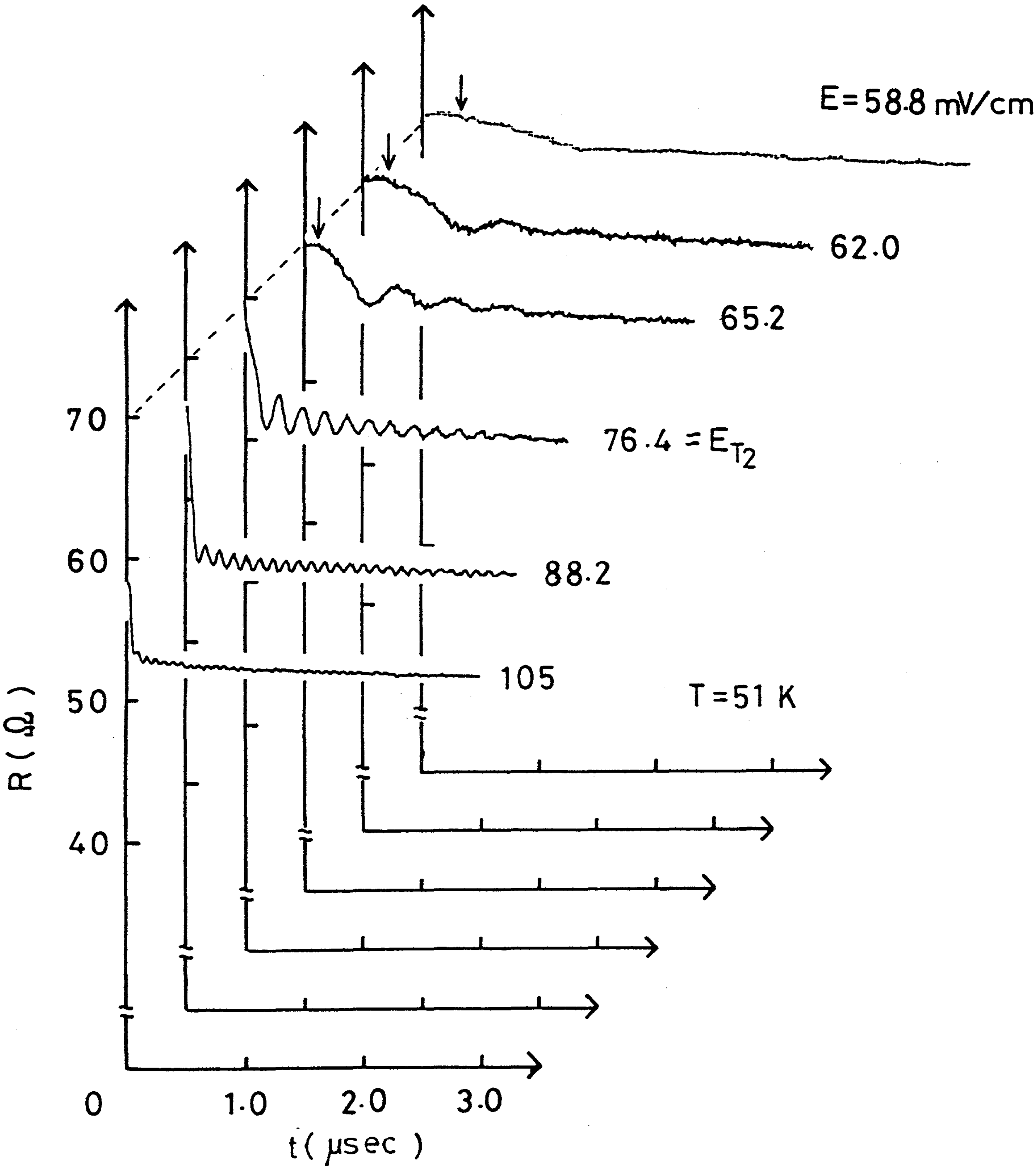

E=58.8 mV/cm
62.0
65.2
76.4 = E_{T_2}
88.2
105
T=51 K
R (Ω)
70
60
50
40
0
1.0
2.0
3.0
t(μsec)

Fig. 6

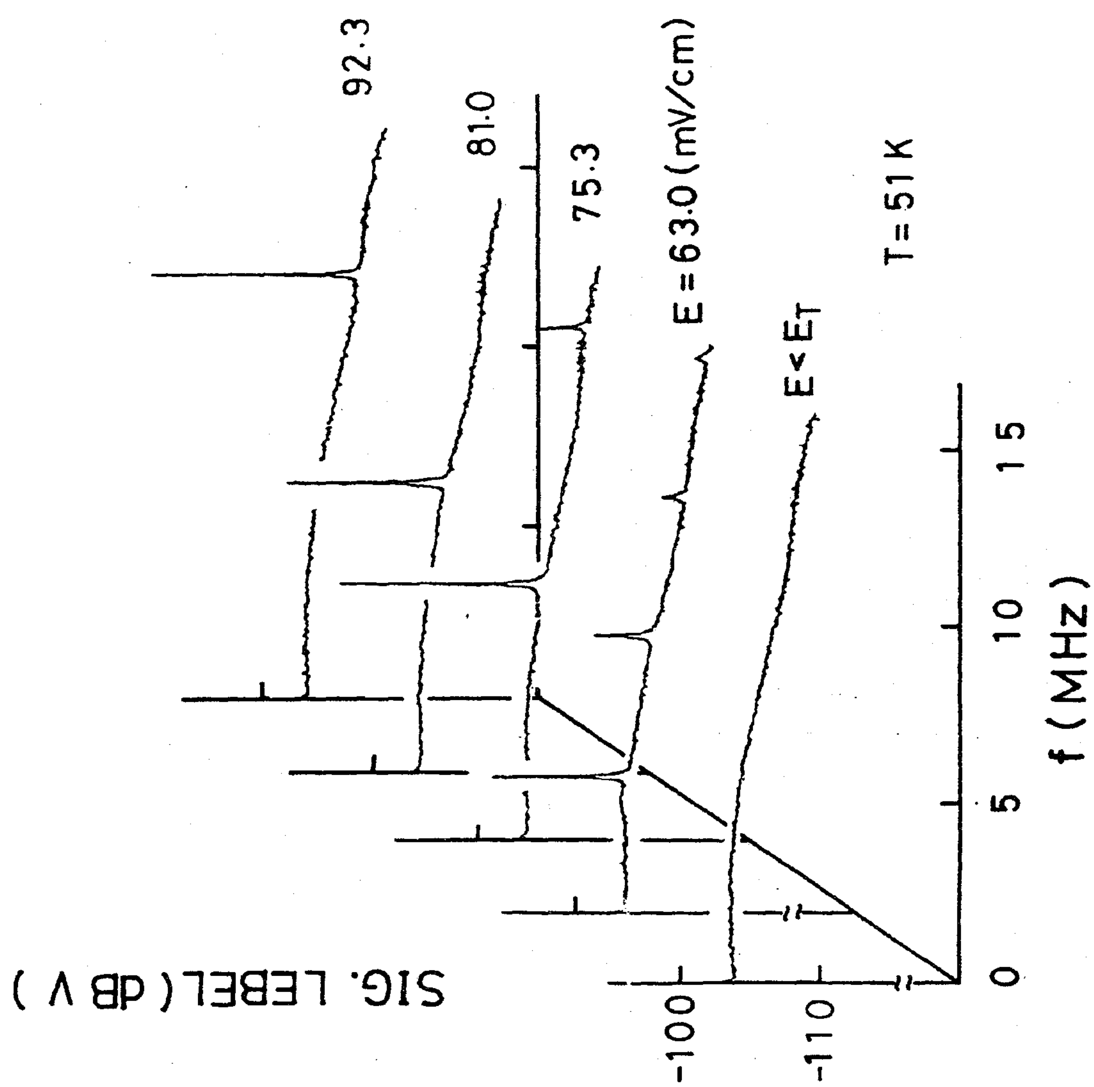

92.3
81.0
75.3
E = 63.0 (mV/cm)
E < E_T
T = 51 K
SIG. LEBEL (dB V)
-100
-110
0
5
10
15
f (MHz)

Fig. 7