

Dielectric Behaviour and Electrical Conduction for Pure and Doped Triglycine Sulphate Single Crystals

Mohamed A. Gaffar and Abd El Aziz A.F. Abd El Aziz

*Physics Department, Faculty of Science, Assiut University,
Assiut, Egypt*

ABSTRACT. The dielectric constant and both D.C. and A.C. electrical conductivity for pure and doped single crystals of TGS are investigated in the temperature range 300-450°K. The influence of the divalent ions; Ni²⁺, Cu²⁺, and Co²⁺ and the trivalent ions; Cr³⁺, and Fe³⁺ on electrical conduction, transition behaviour, transition temperature and dielectric properties in ferro- and paraelectric phases is studied. The difference between the effect of the two groups is more pronounced in the D.C. conduction. The A.C. technique is here proposed to give a clearer picture in the ferroelectric phase. A preliminary trial to study the effect of the pressure on the A.C. conductance is also mentioned.

Dielectric and electrical conductivity properties of triglycine sulphate (TGS) crystals are of great interest both academically and for practical applications.

The dielectric properties of such crystals have been dealt with by many authors (Hoshino *et al.* 1957, Konstantinova *et al.* 1959, Nishioka and Takeuchi 1959, Kamysheva *et al.* 1965, Stankowska and Stankowski 1960, Stankowska 1967, Stankowska *et al.* 1976, Sonin and Gladkiy 1960, Tsedrik *et al.* 1976 and Toyoda *et al.* 1961). The measurements have been carried out under frequencies ranging from one thousand to several mega Hertz. The diversity of the results obtained leaves much to be studied. As a possible source of such divergences, Sonin and Gladkiy (1960) – studying the effect of thickness on the spontaneous polarization-found the dielectric parameters to vary with the thickness of the plates, pointing to surface layers being polarized perpendicular to the polarization direction in the bulk of the crystal. Stankowska and Stankowski (1960) suggested changes in the crystal structure caused by admixtures of foreign ions or permanent changes in domain configuration due to aging.

The study of the influence of doping TGS crystals on the dielectric and electrical properties received much less attention. Tsedrik *et al.* (1976) investigated the effect of Cu^{2+} and Co^{2+} ions on the dielectric constant under different growth temperatures.

Publications on the electrical conductivity of ferroelectrics are scarce specially for TGS single crystals (Gurevich *et al.* 1960, Gurevich and Zheludev 1961 and Hılczler and Michalczyk 1978). However, for these crystals, it is an important physical property required not only for practical applications but also for the interpretation of various physical phenomena such as low frequency dielectric relaxation. Some study on the electrical properties of TGS crystals containing mono-, di-, or trivalent ions was carried out by Toyoda *et al.* (1961).

In the present study we are looking for the influence of the coexistence of some di-, and trivalent ions in the solution used to grow TGS on both dielectric and electrical properties of the grown crystals. Such a study is particularly important because discoveries within the last few years of a number of ferroelectric crystals suggest that hydrogen bonds in these crystals and the presence of ions with particular symmetries, especially those with tetrahedral pyramidal or planer configurations, play a dominant role in the dielectric behaviours.

Experimental

Triglycine sulfate crystals were grown by the authors (Gaffar and Abu El Fadl 1984) from an aqueous solution in the ferroelectric phase near the transition temperature ($\sim 44^\circ\text{C}$) with continuous cooling rate. The samples were cleaved along the cleavage plane from crystals with good faces, no visible defects, and far from the seeding region. The plates obtained in this way were ground for exact orientation. They were then polished with thin silk tissue stretched on a glass surface. The final shape of the samples was rectangular, and 1.5-3 mm. thick. The electrodes were painted onto the polished surfaces using silver paste. The specimens used in all the measurements were exposed to neither preliminary thermal nor electric effects except for a thermal short period for electrode fixation. The samples were mounted in a holder in the measuring thermostat ($\pm 0.05^\circ\text{C}$). The rate of variation of temperature near the transition was about $0.025^\circ\text{C}/\text{min}$.

The dielectric constant was measured under a weak electric field ($< 20 \text{ V/cm}$) at the frequency of 1 kc/sec using an L-C-R bridge. The D.C. electrical conductivity was measured using type 610 C Keithly electrometer. The A.C. conductivity was measured under weak electric field ($< 25 \text{ V/cm}$) at the frequencies 60-500 Hertz.

Results and Discussion

Dielectric Constant

The dielectric constant was measured in the temperature range 300-450°K. The study of the dependence of dielectric constant and the reverse ϵ^{-1} of pure and Co^{2+} , Ni^{2+} , Cu^{2+} , Fe^{3+} and Cr^{3+} doped TGS single crystals on temperature are presented in Figs. 1,2 and 3. At the transition, all crystals manifest a relatively finite sharp peak. Such a finite peak at the Curie point is attributed to either inhomogeneities in temperature, stress distributions and partial clamping of the crystal by the electrodes (Jona and Shirane 1962) or by saturation of polarization against an applied field (Kanzing 1957).

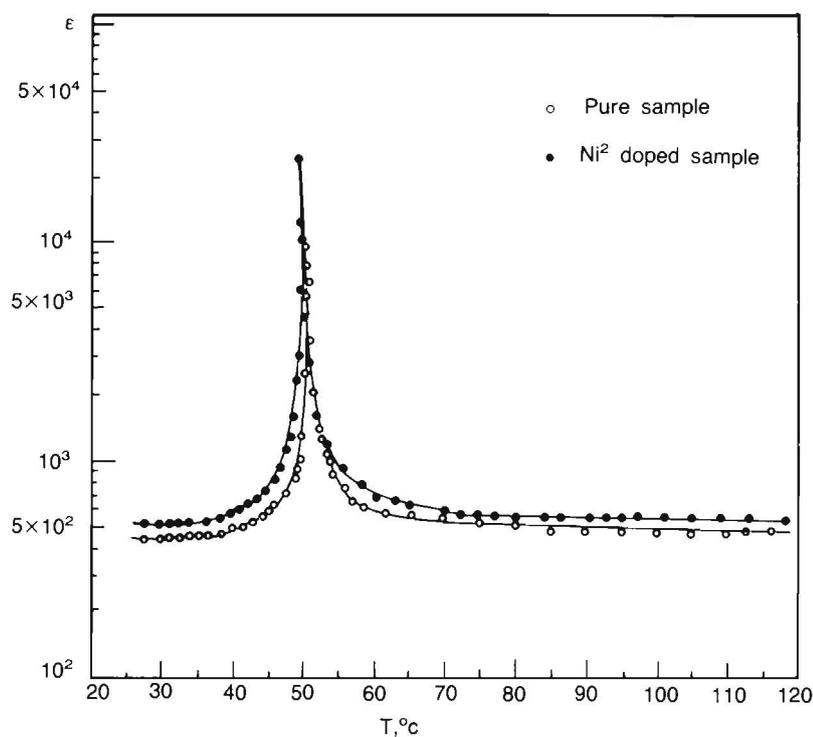


Fig. 1. Dielectric constant of pure and Ni^{2+} doped TGS crystals as function of temperature. The rest of the data is left out for clarification. The behaviour is the same. See details in Fig. 2.

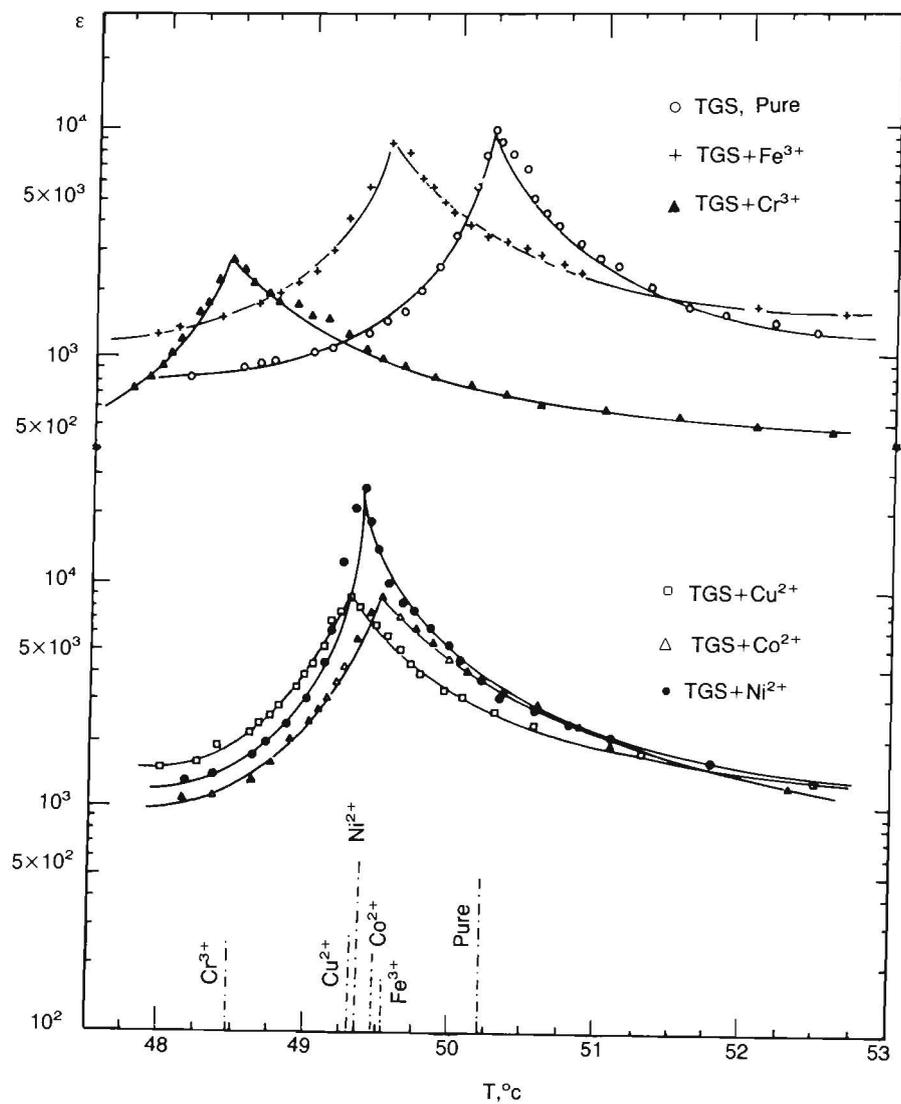


Fig. 2. Dielectric constant versus the temperature in the region of the phase transition of pure and doped TGS single crystals.

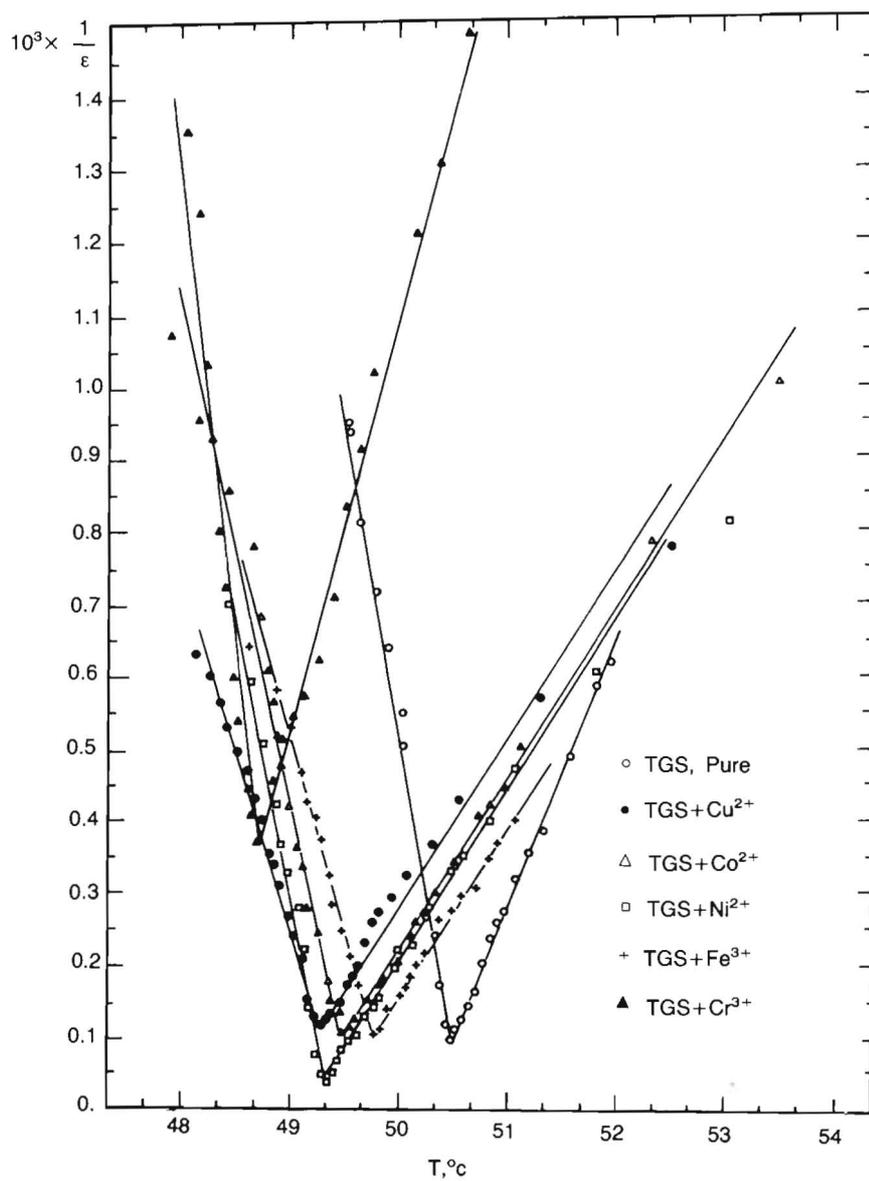


Fig. 3. Temperature dependence of ϵ^{-1} in the vicinity of the Curie point.

In the case of divalent ions; crystals containing Ni^{2+} exhibit the highest value of ϵ at the transition in comparison not only with other doped crystals but also with the pure one. Apparently, the presence of Ni^{2+} ions in TGS single crystals improves the behaviour of such crystals towards an ideal second order phase transition. On the other hand, the existence of Co^{2+} or Cu^{2+} in TGS lowered the ϵ_{max} by about 15% from the pure case. In the work of Tsedrik *et al.* (1976), the presence of the same type of ions in TGS increased ϵ_{max} by about 250%.

For the case of Fe^{3+} and Cr^{3+} a common trend has not been found. The Fe^{3+} doped crystals do not differ much from the pure ones. On the other hand, there is a drastic lowering behaviour of the Cr^{3+} doped crystals in the value of ϵ_{max} . Accordingly, in opposition to the Ni^{2+} case, Cr^{3+} seems to take the crystal away from an ideal second order phase transition.

For each of the five ions involved, a remarkable reduction in T_c is observed compared with that of the pure crystal (Table 1).

Table 1. Parameters describing the dielectric properties of TGS crystals, pure as well as doped with Cu^{2+} , Co^{2+} , Ni^{2+} , Cr^{3+} and Fe^{3+} .

Sample	$C_o \times 10^{-3}$	T_o	T_c	$T_c - T_o$	(Slope) _{Ferro}	$10^{-3} \times \epsilon_{\text{max}}$ At $T = T_c$	$\epsilon_{\text{max}} (T_c - T_o)$ $\times 10^{-3}$
					(Slope) _{para}		
Pure TGS	2.72	50.23	50.48	0.25	2.3	10.548	2.532
TGS + Cu^{2+}	5.21	48.52	49.29	0.77	2.4	7.229	5.278
TGS + Co^{2+}	4.30	49.03	49.49	0.46	2.9	9.461	4.258
TGS + Ni^{2+}	4.52	49.06	49.35	0.29	3.3	16.560	4.306
TGS + Cr^{3+}	1.67	48.09	48.69	0.60	2.6	2.930	1.670
TGS + Fe^{3+}	4.50	49.26	49.80	0.54	2.4	9.176	4.680

Apparently, there is an obvious similarity in the transition temperature of the three divalent ions used (Cu^{2+} , Ni^{2+} and Co^{2+}), about $49.4 \pm 0.1^\circ\text{C}$ which might be explained by an almost identical ionization activity. However the rather different response of the two trivalent ions, Fe^{3+} and Cr^{3+} may be due to their different ionization activity under the same pH value used. In addition, the Cr^{3+} complex showed the lowest T_c value.

In a limited temperature range on both sides of the Curie point T_c , the dependence of ϵ^{-1} on T is practically linear. In the paraelectric region, the Curie-Wiess law holds, though the slopes of the lines are rather different

indicating a dependence on the kind of ion's activity involved. While, in the ferroelectric region, the difference in slopes might be attributed to differences in the domain structure of the crystal under study. According to Zhukov *et al.* (1967), the ferroelectric domains of TGS are strongly changed under the influence of Ni^{2+} and Cr^{3+} ions.

According to the theory (Jona and Shirane 1962) the slopes in the ferroelectric region is twice that in the paraelectric region. If one is to take into account the difference between the adiabatic (ϵ_S) and the isothermal (ϵ_T) dielectric constant in the ferroelectric region, the ratio of the slopes would be about 2.4.

In our study, the pure TGS and some of the doped crystals show an agreement with the theory. On the other hand, a deviation from the predicted result is found especially for the Co^{2+} and Ni^{2+} containing crystals.

The result for the Co^{2+} doped crystal is not far from the result of Tsedrik (Tsedrik *et al.* 1976), (2.7 ± 0.2). However, in case of crystal doped with Ni^{2+} the resultant discrepancy may be explained by the suggestion (Jona and Shirane 1962) that in multi-domain crystals, below the transition temperature, the domains may be polarized antiparallel to each other which may cause partial clamping of the crystal, and hence contributes to the internal electric field.

According to Wieder (1959), under the influence of an external electric field E , ϵ_{max} and T_{max} have the following relations:

$$\epsilon_{\text{max}} = \frac{4\pi}{3} \left(\frac{\beta}{2}\right)^{-\frac{1}{2}} E^{-\frac{1}{2}}$$

$$(T_{\epsilon_{\text{max}}} - T_0) = \frac{3}{8\pi} C_0 \left(\frac{\beta}{2}\right)^{\frac{1}{2}} E^{\frac{1}{2}}$$

where β is the second coefficient in the expansion of the thermodynamic potential in powers of polarization. Hence the resultant equation:

$$\epsilon_{\text{max}} (T_{\epsilon_{\text{max}}} - T_0) = 0.5 C_0$$

holds for second-order phase transition.

ϵ_{max} is affected by two opposing factors, the relaxation of interaction of crystal defects which leads to the decrease of $T_{\epsilon_{\text{max}}}$; and the appearance of internal fields causing the maximum shift of the position of ϵ_{max} towards higher temperature and which is accompanied by a decrease in the magnitude of ϵ_{max} . The internal electric field created by the structural or chemical defects has an effect which is similar to

an external electric field. This prompted us to apply the same idea to our results. The results given in Table 1 show a straight line behaviour, as expected, but with twice the value of the constant:

$$\epsilon_{\max} (T_{\epsilon_{\max}} - T_0) \approx 1.00 C_0$$

This is shown in Fig. 4. Thus we may conclude that the internal electric field (for the monoclinic system- our case) has twice the effect on the value of the dielectric constant ϵ_{\max} .

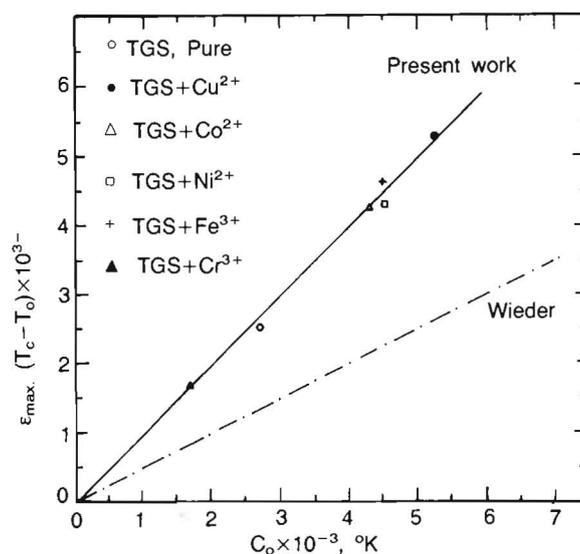


Fig. 4. Relation between dielectric parameters at maximum value and Curie-Weiss constant.

Electrical Conductivity

D.C. Electrical conductivity

The data reported for the electrical conductivity of TGS single crystals diverge considerably in their anomalous behaviour at the Curie point and the activation energies in the ferroelectric and paraelectric phases. The Curie point anomaly shows up as a kink connecting two straight lines (Hilczer and Michalczyk 1978), as different types of discontinuity (Gurevich *et al.* 1960), or even with hysteresis (Gurevich and Zheludev 1961), in the 1σ vs. T^{-1} dependence function. The

activation energies along the three crystallographic axes have their share of the diversity (Toyoda *et al.* 1961, Gurevich *et al.* 1960, Gurevich and Zheludev 1961 and Hilczer and Michalczyk 1978).

We begin by considering the pure crystal. The D.C. electrical conductivity was measured in the a, b and c crystallographic directions and the results of its temperature dependence are shown in Fig. 5. In the paraelectric phase, the data

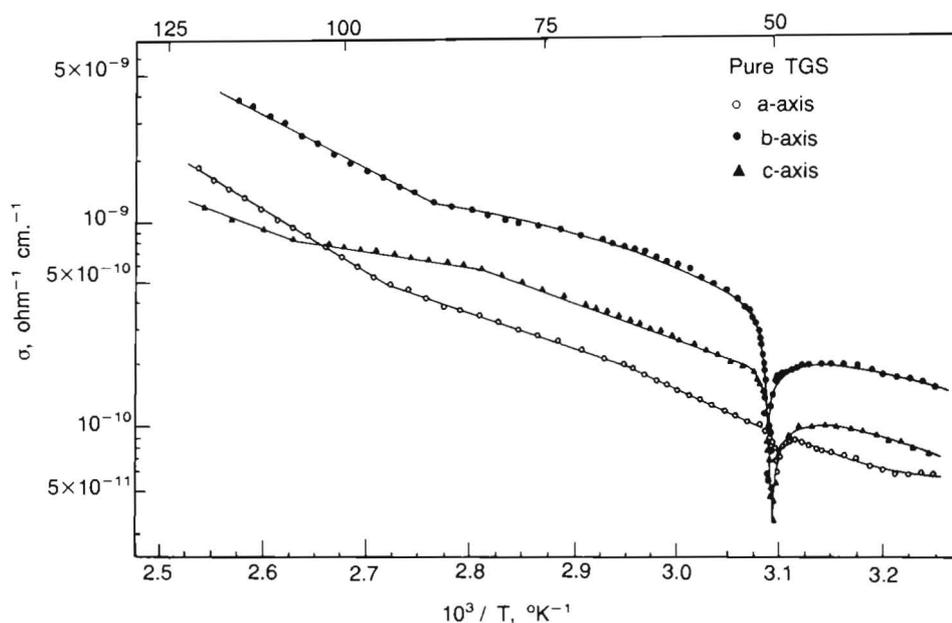


Fig. 5. D.C. electrical conductivity of pure TGS as a function of temperature in the three crystallographic directions.

can be segmented into three straight lines with kinks. The small temperature interval of the ferroelectric phase can be represented by another straight line. A pronounced anomaly in σ at the Curie point associated with a decrease in the value of the electrical conductivity and a variation in the activation energy before and after T_c indicate a change in the conduction mechanism as recorded, see Table 2. Also, one cannot fail to notice the difference in T_c for the three axes.

Table 2. Parameters describing the D.C. electrical conductivity of TGS crystals, pure as well as doped with Cu^{2+} , Co^{2+} , Ni^{2+} , Cr^{3+} and Fe^{3+} .

Sample	W (ferro.) (e.v.)	W (para) (e.v.)			T_c	σ at T_c
		W_1	W_2	W_3		
Pure TGS	0.141	0.545	0.203	0.600	50.7	5.68×10^{-11}
TGS + Cu^{2+}	0.308	0.488	0.166	1.038	49.6	3.40×10^{-11}
TGS + Co^{2+}	0.138	0.525	0.123	0.727	49.8	1.82×10^{-11}
TGS + Ni^{2+}	0.143	0.408	0.237	0.976	49.6	3.67×10^{-11}
TGS + Fe^{3+}	0.388	0.374	0.202	0.588	49.7	3.40×10^{-10}
TGS + Cr^{3+}	0.392	0.601	0.179	0.547	48.6	8.30×10^{-10}

Figure 6 shows the results of repetitive measurements along the b-axis. From run to run neither the general behaviour nor the temperature of transition are changed ($T_c = 50.5 \pm 0.1^\circ\text{C}$). The only difference is that the anomaly at the transition temperature becomes more pronounced.

The overall trend of increasing conductivity with temperature is usually attributed to the increase in number of carriers, albeit depending on the ambient temperature. As for the anomaly groove at T_c we propose the idea that this is due to the phase-transition local electric field anomaly felt by the carriers and which is due to the crystallographic transition at T_c .

Second, we deal with the doped crystals. It has been reported that the electrical conductivity of TGS crystals grown from solutions containing an excess (above the stoichiometric ratio) of sulfuric acid depends strongly on the number of the excess sulfuric ions (Zheludev 1971). The conductivity of TGS crystals grown from solution of stoichiometric composition is most likely to be due to the presence accidental impurities. This is confirmed by the observation that successive recrystallization reduces their electrical conductivity (Zheludev 1971). Consequently, the presence of di- or trivalent ions even in a low concentration in the solution of growth of TGS must affect the electrical conductivity of such crystals.

The temperature dependence of the electrical conductivity of doped TGS crystals is presented in Fig. 7. From the figure, the following conclusions could be drawn.

1. The electrical conductivity shows the same groove at T_c for all crystals containing divalent ions, a behaviour which is identical to that of the pure crystal. One has to notice again the peculiarity in the Ni^{2+} doped crystal as in the dielectric

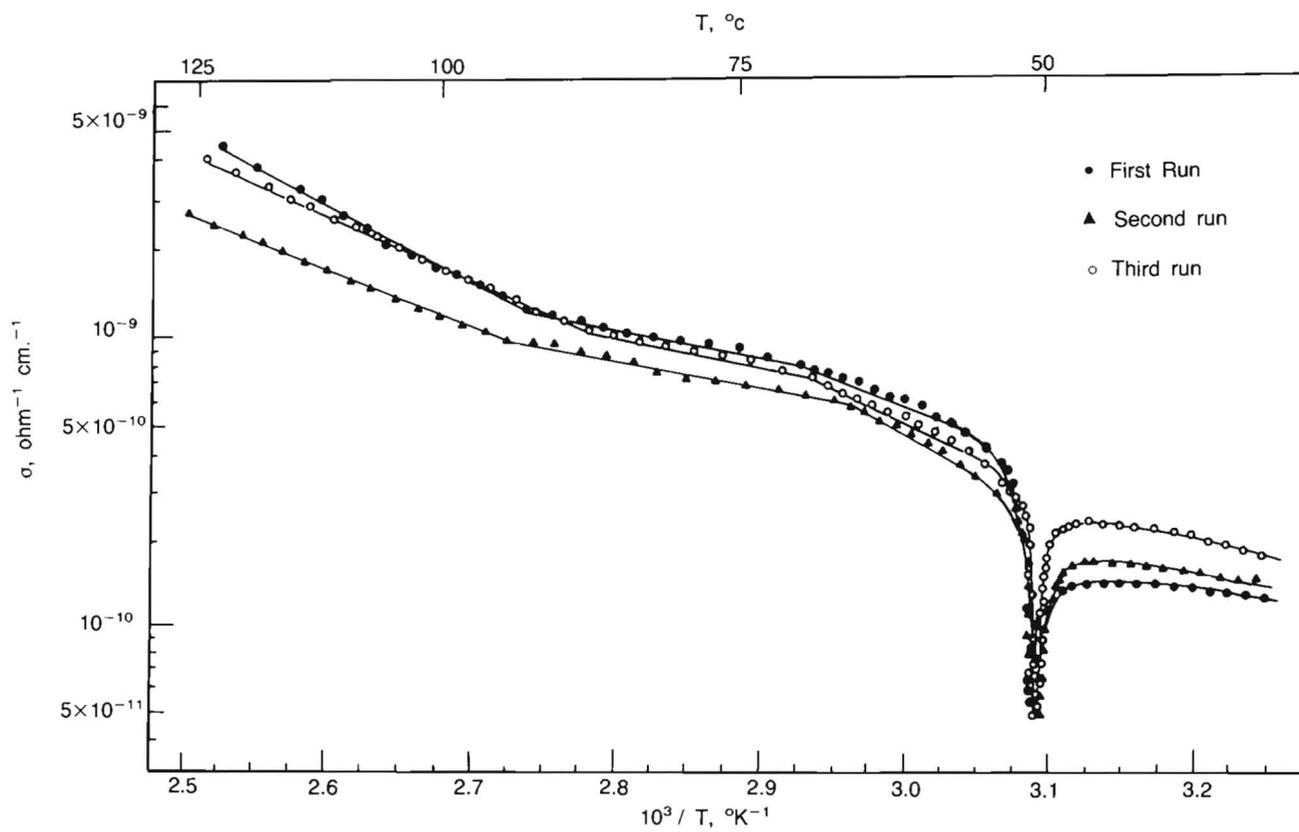


Fig. 6. Repetitive measurements of the D.C. electrical conductivity along the b-axis as a function of temperature.

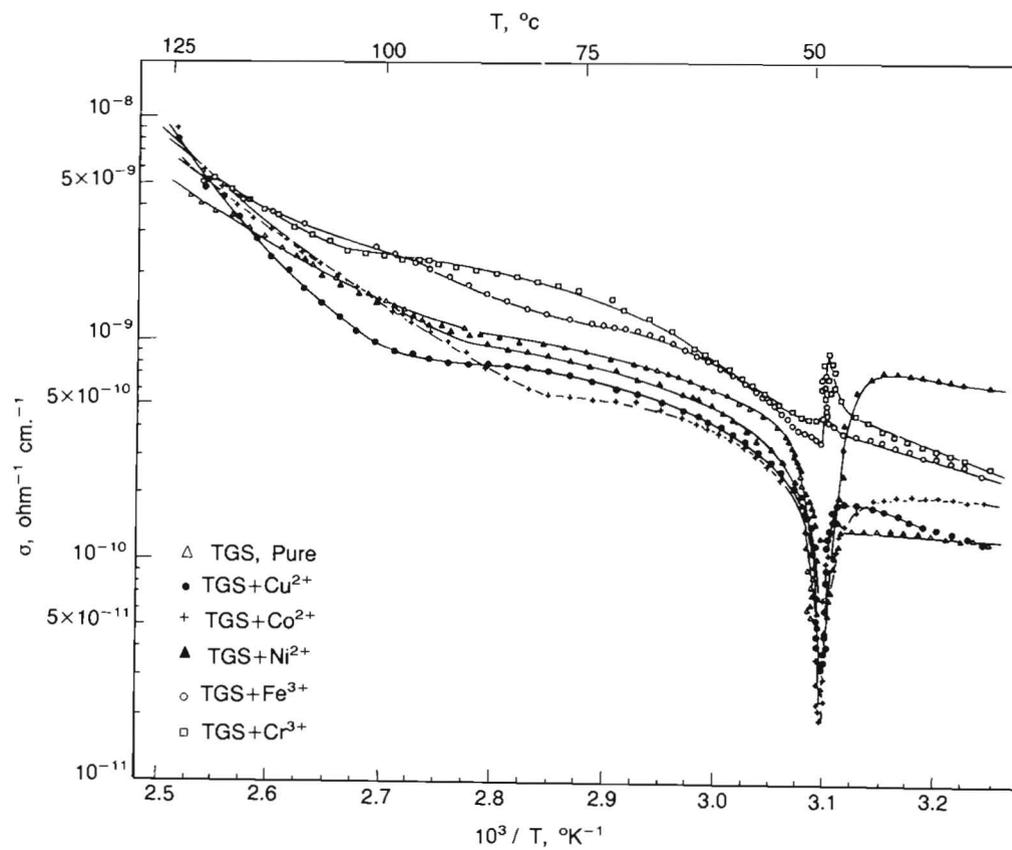


Fig. 7. Temperature behaviour of the D.C. electrical conductivity of pure and Ni^{2+} , Co^{2+} , Cu^{2+} , Fe^{3+} and Cr^{3+} doped TGS single crystals.

measurements. On the other hand, the presence of trivalent ions manifests itself as a spike in the electrical conductivity at T_c .

2. Within experimental error, the values of T_c for all the crystals are in accordance with those obtained by dielectric measurements.

We discuss here the presence of doping ions. Their presence according to Krajewski and Riad (1975), results in a lattice distorted from the perfect one. Zhukov *et al.* (1967) reported a marked change in the domain structure beside an inhomogeneity in the ions distribution throughout the crystal. The addition of divalent ions will result to some extent, in the formation of complexes (Lösche and Windsch 1965) which is the reason for distortion. This may be accompanied by interstitial implantation. The complex formation with divalent ions will result in emancipation of two hydrogen ions (the carriers). This complex formation depends on the chemical activity and concentration in the solution of the ion, pH value and temperature of crystallization. In the crystal, there may be some tendency to form complexes by raising its temperature in the ferroelectric region. It is clear now that Ni^{2+} ion -according to this hypothesis- is the most active one. The general behaviour of the divalent ion doped crystals resembles that of the pure one, resulting in an equal change in T_c due to distortion.

The temperature dependence of complex formation in the trivalent ions doped crystals seems to be of such a magnitude that it will compensate or even overcome the anomalous local field effect at T_c , hence the "spike" character in their conductivity curve.

A more comprehensive and detailed study of the electrical conduction in TGS is needed. We have carried out a preliminary experiment on the pure crystal down to 77°K. We noticed that there are reverses in polarity around 110 and 140 K. These correspond to the temperatures of the phase transitions reported by Al-Eithan *et al.* (1982) for TGS using Raman spectroscopy. A confirmation of the existence of these phase transformation needs more detailed study. This is in progress in our laboratory.

A.C. Electrical conductivity

The additional A.C. conductivity measurements were made in the hope of shedding some light on the domain structure.

The measurements were carried out for pure TGS at different frequencies (60-500 c/sec) along the b-axis with an A.C. field < 30 V/cm. The results are shown in Fig. 8. It is clear from such measurements that they confirm our dielectric ones, compare Figs. 2 and 8. The relation between σ at T_c and the frequency can be represented approximately in this limited frequency region by a straight line (Fig. 11):

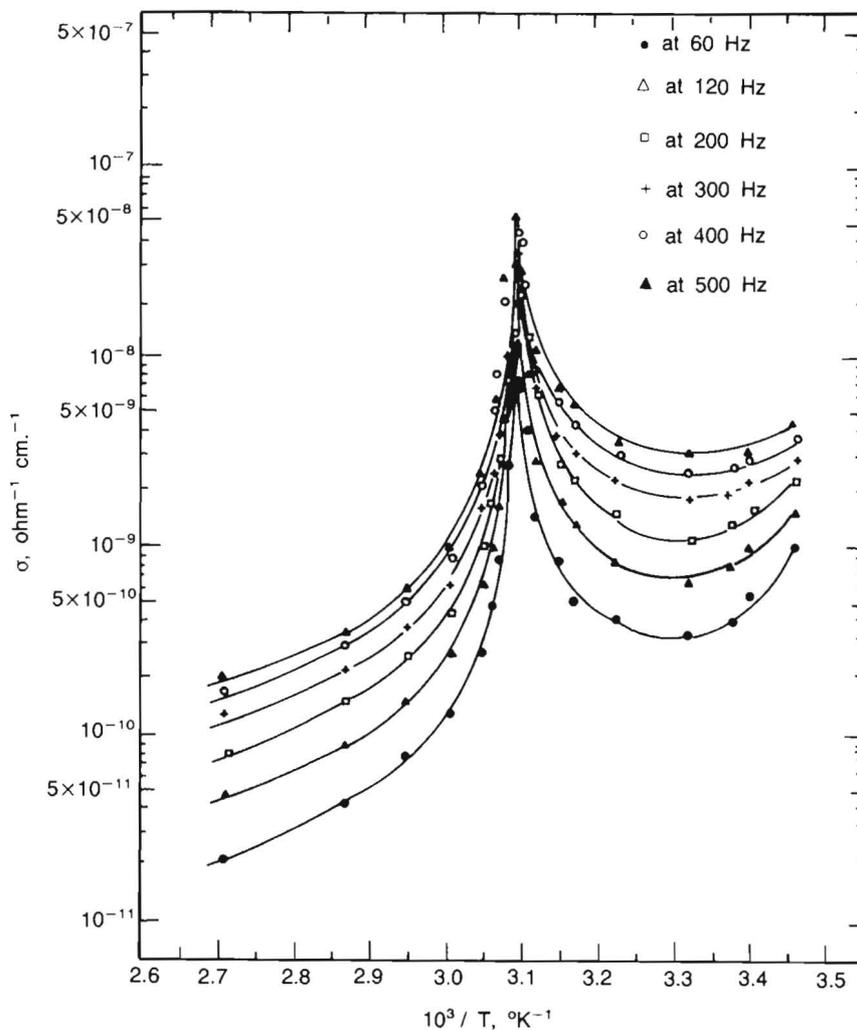


Fig. 8. A.C. electrical conductivity of pure TGS along the b-axis as function of temperature at different frequencies.

$$\sigma_{T_c} \times 10^9 = 1.1 f + 6.2$$

A second point of study is to see the possibility of detection of hysteresis as reported by Gurevich (Gurevich and Zheludev 1961).

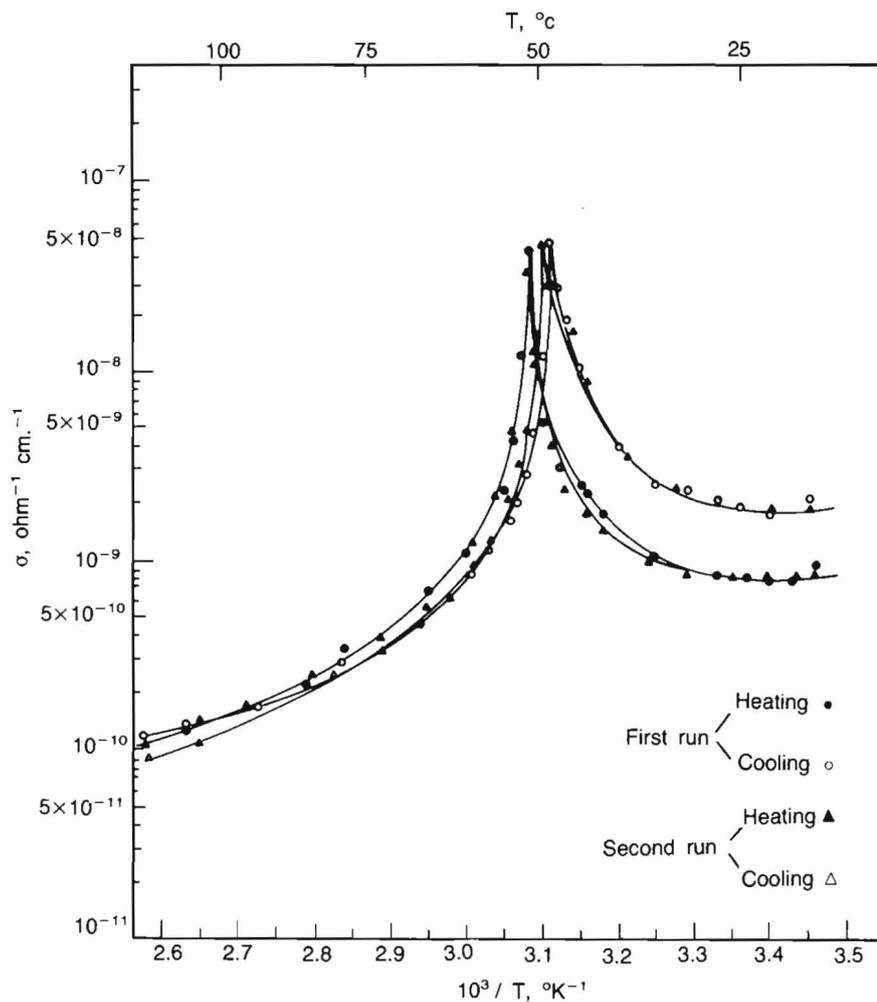


Fig. 9. Two successive heating-Cooling runs for the A.C., electrical conductivity indicating the presence of hysteresis.

The results presented in Fig. 8 show a difference in the value of T_c ($\Delta T_c \approx 3.0^\circ\text{C}$) pointing to hysteresis existence. Consequently, one may conclude that TGS may exhibit some features of the first-order phase transition.

A third and important result is the A.C. measurement on the doped crystals. This is shown in Fig. 10. It is significant to see now the different behaviour of the

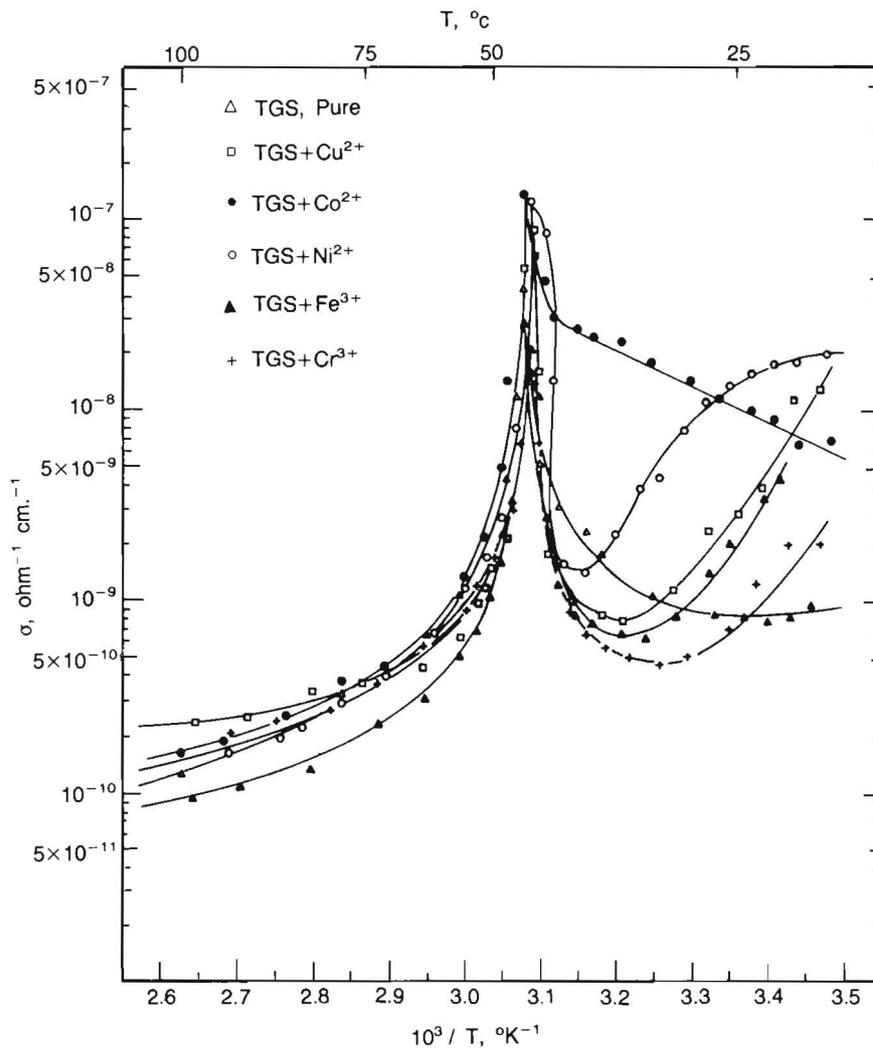


Fig. 10. The temperature dependence of the A.C. electrical conductivity of pure and doped TGS single crystals.

doped crystals in the ferroelectric region. Apparently, the A.C. conductivity measurement is a good tool to detect differences in domain configuration.

The last point is concerned with a preliminary examination of the effect of small pressure applied to TGS crystals on the conductance. We show our results for

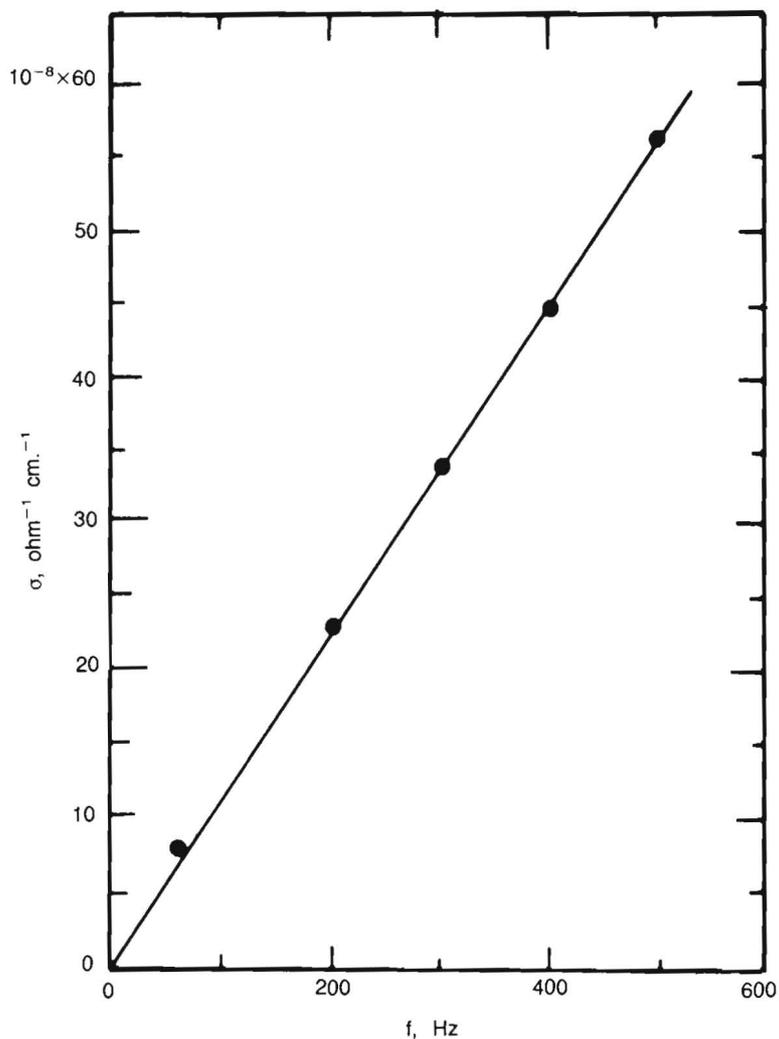


Fig. 11. The dependence of conductivity at the transition on frequency of the measuring field.

the pure crystal in Fig. 12 for different frequencies. It is clear that for low frequencies the effect of pressure is predominant. At a glance this may explain some of the differences in data of TGS. This point is being investigated further in our laboratory.

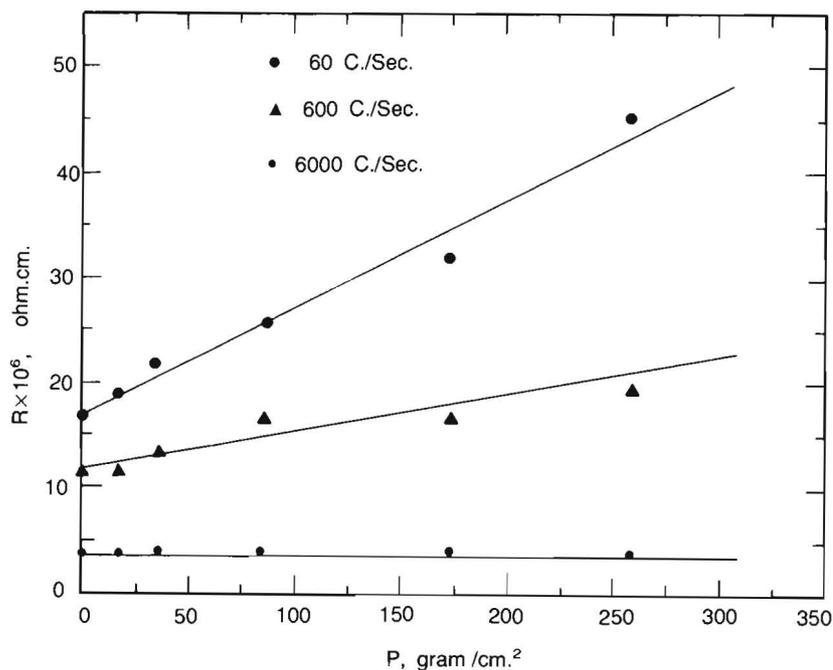


Fig. 12. Effect of a small pressure acting on the contacts on the measuring A.C. electrical conductivity.

References

- Al-Eithan, E.Y., Bates, A.R. and Gough, W. (1982) A new phase transition in ferroelectric triglycine sulphate, *Raman Spectros. Proc. Int. Conf. 18th.*, Lascombe, (ed.) Huang Pham V. Wiley; Chichester U.K.: 471-472.
- Gaffar, M.A. and Abu El-Fadl, A. (1984) Growth of pure and doped triglycine sulphate single crystals, *XIIIth. Cong. International Union of crystallography*, Hamburg, FRG 9-18 August: C-186.
- Gurevich, V.M., Zheludev, I.S. and Rez, I.S. (1960) Electrical conductivity of a single crystal of triglycine sulfate, *Kristallografiya* 5: 133-136. Translated from *Kristallografiya* 5: 142-145.
- Gurevich, V.M. and Zheludeve, I.S. (1961) A study of the phase transition of a triglycine sulfate monocrystal at the Curie point by measuring the electrical conductivity, *Kristallografiya* 6: 110-112. Translated from *Kristallografiya* 6: 135-137.
- Hilczler, B. and Michalczyk, M. (1978) Electrical conductivity of TGS, pure and with lattice defects, *Ferroelectrics* 22: 721-723.
- Hoshino, S., Mitsui, T., Jona F. and Pepinsky, R. (1957) Dielectric and thermal study of triglycine sulfate and triglycine fluoberyllate, *Physical Review* 107: 1255-1258.
- Jona, F. and Shirane, G. (1962) *Ferroelectric Crystals*, Macmillan New York, pp. 29-30.

- Kamysheva, L.N., Kovalenko, A.N. and Minaeva, T.A.** (1965) Non-linear properties of triglycine sulfate, *Izv. Akad. Nauk SSSR Ser. Fiz.* **29**(11): 1994-1995.
- Kanzig, W.** (1957) *Solid State Physics Vol. 4 "Ferroelectrics and Antiferroelectrics"*, p. 14.
- Konstantinova V.P., Silvestrova I.M. and Aleksandrov K.S.** (1959) The preparation of crystals of triglycine sulfate and their physical properties, *Kristallografiya* **4**: 69-73.
- Krajewski, T. and Riad, M.A.** (1975) Thermal diffusivity of copper doped TGS (Triglycine sulfate) Crystals, *Acta Physica Polonica* **48A**: 649-656.
- Lösche, A. and Windsch W.** (1965) EPR. Untersuchungen an Kupferdotierten Triglyzinsulfat-Einkristallen, *Phys. Stat. Sol.* **11**: K55-K57.
- Nishioka, A. and Takeuchi, M.** (1959) Dielectric properties of triglycine sulfate single crystals at 9000 Mc/sec region, *J. Phys. Soc. Japan* **14**: 971.
- Sonin, A.S. and Gladkiy, V.V.** (1960) Relation between thickness and dielectric parameters for plates of Triglycine sulfate, *Crystallografiya* **5**: 145-147. Translated from *Soviet Phys. Crystal.* **5**: 136-138.
- Stankowska, J.** (1967) Ageing process in triglycine sulphate single crystals, *Acta Physica Polonica* **31**: 527-554.
- Stankowska, J. and Stankowski, J.** (1960) Investigation of ageing in triglycine sulfate, *Acta Phys. Polon.* **19**: 217-225.
- Stankowska, J., Czarnecka, A., and Kafuba, M.** (1976) Dielectric properties of deuterized TGS and TGSe crystals, *Acta Phys. Pol.* **A50**(6): 823-830.
- Toyoda, H., Tanaka, Y. and Shiokowa W.** (1961) Growth and electrical properties of ferroelectric glycine sulfate single crystals, *Review of the electrical communication Laboratory* **9**: 485-496.
- Tsedrik, M.S., Ulasen, V.N. and Zaborovski, G.A.** (1976) Triglycine sulphate single crystals growing doped with copper and cobalt ions and study of their dielectric properties, *Kristall und Technik* **11**: 49-58.
- Wieder, H.** (1959) Ferroelectric properties of colemanite, *J. App. Phys.* **30**: 1010-1018.
- Zheludev, I.S.** (1971) *Physics of Crystalline Dielectrics*, Vol. 2, Dlenum Press, New York, London, p. 493.
- Zhukov, O.K., Gridnev, S.A. and Kostsov, A.M.** (1976) Effect of small impurities of nickel and chromium ions on some properties of triglycine sulfate VINITI. 3587-3596 (In Russian).

(Received 01/06/1986;
in revised form 24/01/1987)

سلوك العزل والتوصيل الكهربائي لبلورات كبريتات ثلاثي الجليسين نقية وأخرى مطعمة بالشوائب

محمد عبدالعزيز جعفر^١ و عبدالعزيز أبو الفضل عبدالعزيز

قسم الطبيعة - كلية العلوم - جامعة أسيوط - أسيوط - مصر

تمت في هذا البحث دراسة ثابت العزل الكهربائي في إتجاه المحور القطبي لبلورات نقية وأخرى مطعمة بأحد الأيونات ثنائية أو ثلاثية التكافؤ Cu^{2+} , Co^{2+} , Cr^{3+} , Fe^{3+} , Cr^{3+} في المدى الحراري بين 300 ، 450 درجة مطلقة. أظهرت الدراسة أن جميع البلورات تبدي نفس السلوك لتغير ثابت العازل ϵ بتغير درجة الحرارة T حيث تزداد قيمة ϵ بصورة حادة إلى نهاية عظمى ϵ_{\max} عند درجة حرارة الانتقال الطوري T_c . تختلف قيمة ϵ_{\max} كما تختلف T_c للبلورات المطعمة بالشوائب فيما بينها كما أنها تختلف عن قيمة T_c لبلورات النقية. يطبع ثابت العازل قانون كوري - فايس في طور الباراكهربية. في طور الفروكهربية تختلف قيم ϵ من بلورة إلى أخرى وهو أمر يعزى إلى الاختلاف في هيئة مناطق الإستقطاب. وجد أن النسبة بين ميل الخطوط المستقيمة الممتدة للعلاقة بين ϵ^{-1} ودرجة الحرارة في كل من طوري الفرو- والباراكهربية مطابقة للقيم النظرية، كذلك وجد أن العلاقة بين ثابت كوري C_0 ، $\epsilon_{\max} (T_c - T_0)$ حيث T_0 هي درجة حرارة كوري - فايس للبلورات المختلفة هي علاقة خط مستقيم مما يوحي بأن الشوائب المضافة أدت إلى ظهور مجال إنحيازي داخلي مماثل للمجال الإنحيازي الداخلي الذي ينشأ عن وقوع البلورة تحت تأثير مجال كهربائي خارجي.

تمت في هذا البحث أيضاً دراسة التوصيل الكهربائي في مجال كهربائي مستمر وآخر متردد. في الحالة الأولى أجريت الدراسة على البلورات النقية في الإتجاهات الإحداثية الثلاثة في المدى الحراري المشار إليه، بينما كانت الدراسة في إتجاه المحور القطبي فقط

(١) العنوان الحالي: قسم الفيزياء - كلية العلوم - جامعة قطر - ص.ب ٢٧١٣

بالنسبة للبلورات المطعمة بالشوائب. دلت النتائج على حدوث تغير حاد في قيمة التوصيل الكهربى عند درجة حرارة الإنتقال الطوري بكيفية تختلف في حالة البلورات المطعمة بشوائب ثلاثية التكافؤ عنها في حالة البلورات المطعمة بشوائب ثنائية التكافؤ والتي يتفق سلوكها مع سلوك البلورات النقية مما يوحي بأن هيئة المركبات الناتجة عن شغل الشوائب ثلاثية التكافؤ لأماكن في الشبكية البلورية أعقد من مثيلتها التي تتكون في حالة الشوائب ثنائية التكافؤ. أثبتت الدراسة أن المعالجات الحرارية المتكررة تؤدي إلى اتفاق النتائج المأخوذة في التجارب المتعاقبة، كذلك تبين أن هناك تخلف كهربى صغير مما يشير إلى وجود ملامح لتغير في الطور من الرتبة الأولى. اتفقت قيم درجة حرارة الإنتقال الطوري عند قياس التوصيل الكهربى مع القيم التي حصلنا عليها عند قياس ثابت العازل الكهربى كما تفقت قيم معامل التنشيط في الحالات المختلفة مع القيم المنشورة في أبحاث سابقة. إتضح من الدراسة أيضاً أن تغير التوصيل الكهربى باستخدام مجال كهربى متردد مع تغير درجة الحرارة يتفق من ناحية الشكل مع تغير ثابت العازل بتغير درجة الحرارة، بالإضافة إلى هذا تبين أن هناك علاقة خطية تربط بين التوصيل الكهربى وتردد التيار الكهربى المستخدم.