Broadband dielectric spectroscopy of mixed CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ crystals

J.Macutkevic$^1$, J.Banys$^2$, R. Grigalaitis$^2$, and Yu. Vysochanski$^3$

$^1$Semiconductor Physics Institute, A. Gostauto 11, 2600 Vilnius, Lithuania
$^2$Faculty of Physics, Vilnius University, Sauletekio 9, Vilnius LT-10222, Lithuania and
$^3$Institute of Solid State Physics and Chemistry of Uzhgorod University, Ukraine

(Dated: May 8, 2008)

In this article mixed CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ crystals were investigated by broadband dielectric spectroscopy (20 Hz - 3 GHz). The complete phase diagram has been obtained from these results. The phase diagram of investigated crystals is strongly asymmetric - the decreasing of ferroelectric phase transition temperatures in CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ is much more flat with small admixture of sulphur than with small admixture of selenium. In the middle part of the phase diagram ($x=0.4$-$0.9$) the dipolar glass phase has been observed. In boundary region between ferroelectric order and dipolar glass disorder with small amount of sulphur ($x=0.2$-$0.25$) at low temperatures the nonergodic relaxor phase appears. The phase diagram was discussed in terms of random bonds and random fields.

PACS numbers: 77.22.-d, 77.80.-e, 77.22.Gm, 81.30.-t

I. INTRODUCTION

Solid systems present many interesting types of phase transitions, with ferro, antiferro, or modulated long range order at lower temperatures. Disordered cooperative systems have also attracted a lot of attention. Nonergodic relaxor, dipolar glass phases or coexistence of ferroelectric transitions showed only nearly second order phase transition $\Delta T_{\text{rel}}$ associated with the

$\sigma_{DC}$ follows the Arrhenius law with the activation energy $E_A = 0.73$ eV $^5$ and more detailed investigations showed $E_A=0.635$ eV $^6$.

The results of dielectric investigations of CuInP$_2$S$_6$ showed two phase transition: a second-order one at $T_c=248$ K and a first-order transition at $T_c=236$ K $^7$. The results followed to the conclusion that an incommensurate phase occurs between $T_t$ and $T_c$. However, the calorimetric investigations showed only a broad phase transition between 220 and 240 K in this compound $^8$. More accurate broadband dielectric investigations showed only nearly second order phase transition at $T_c=226$ K $^9$. From a single-crystal X-ray diffraction study follows that the high- and low-temperature structures of CuInP$_2$S$_6$ (trigonal space group P-31c and P31c, respectively) are very similar to those of CuInP$_2$S$_6$ in the paraelectric and ferrielectric phases, with the Cu$^I$ off-centering shift being smaller in the former than in the latter $^3,8$. There the thermal evolution of the cell parameters of CuInP$_2$S$_6$ was obtained by full profile fits to the X-ray diffraction files. Both cell parameters $a$ and $c$ slightly decrease on cooling, and $c$ parameter shows a local minimum at $T=226$ K. This behaviour is quite different from the anomalous increases found in the cell parameters of CuInP$_2$S$_6$ when heating through the transition $^1,3$.

The important feature of selenides is the higher covalence degree of their bonds. Evidently, for this reason the copper ion sites in the low-temperature phase of CuInP$_2$S$_6$ are displaced only by 1.17 Å $^8$ from the middle of the structure layers in comparison with the corresponding displacement 1.6 Å for CuInP$_2$S$_6$ $^1$. These facts enable to assume that the potential relief for copper ions in CuInP$_2$S$_6$ is shallower than for its sulphide
analog. Presumably, for this reason the structural phase transition in the selenide compound is observed at lower temperature than for the sulphide compound. Preliminary dielectric investigations of CuInP$_2$(S$_{x}$Se$_{1-x}$)$_6$ crystals are presented in [11, 12]. The data in [11] is measured only at frequency 10 kHz and the paper [12] contain data only on one compound - CuInP$_2$(S$_{0.7}$Se$_{0.3}$)$_6$.

The aim of this paper is to investigate phase diagram of mixed CuInP$_2$(S$_{x}$Se$_{1-x}$)$_6$ crystals via broadband dielectric spectroscopy. We showed that in mixed crystals with the increasing amount of impurities two smearing of ferroelectric phase transition scenarios are possible: ferroelectric - inhomogeneous ferroelectric - dipolar glass or ferroelectric - relaxor - dipolar glass.

II. EXPERIMENTAL

Crystals of CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ were grown by Bridgman method. For the dielectric spectroscopy the plate like crystals were used. All measurements were performed in direction perpendicular to the layers. The complex dielectric permittivity $\varepsilon^*$ was measured using the HP4284A capacitance bridge in the frequency range 20 Hz to 1 MHz. In the frequency region from 1 MHz to 3 GHz measurements were performed by a coaxial dielectric spectrometer with vector network analyzer Agilent 8714ET. All measurements have been performed on cooling with controlled temperature rate 0.25 K/min. Silver paste has been used for contacting.

III. RESULTS AND DISCUSSION

A. Influence of small amount of sulphur to phase transition dynamics in CuInP$_2$Se$_6$ crystals

A small amount of admixture can significant changes properties of ferroelectrics. In mixed CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ crystals with $x \leq 0.1$ the ferroelectric phase transition is observed (Fig. 1). Here the dielectric permittivity maximum temperature ($T_m$) is frequency-dependent only at higher frequencies (above 1 MHz). The phase transition temperature can be defined by $T_m$ at low frequencies (below 1 MHz). The temperature behaviour of the dielectric dispersion of CuInP$_2$Se$_6$ crystals with a small admixture of sulphur (Fig. 2) is very similar to the dielectric dispersion of pure CuInP$_2$Se$_6$ crystals [9]. At higher temperatures ($T >> T_c$) the dielectric dispersion reveals in $10^8$ - $10^{10}$ Hz frequency range. With decreasing temperature the dielectric dispersion become broader and appears at lower frequencies. At lower temperatures ($T << T_c$) the dielectric dispersion remains in the $10^8$ - $10^{10}$ Hz frequency range and only its strength decreases on cooling.

More information about the phase transition dynamics can be obtained by analysis the dielectric dispersion with the Cole-Cole formula

$$\varepsilon^*(\nu) = \varepsilon_\infty + \frac{\Delta \varepsilon}{1 + (i\omega \tau_{CC})^{1-\alpha_{CC}}}.$$  \hspace{1cm} (1)

where $\Delta \varepsilon$ represents dielectric strength of the relaxation, $\tau_{CC}$ is the mean Cole-Cole relaxation time, $\varepsilon_\infty$ represents the contribution of all polar phonons and electronic polarization to the dielectric permittivity and $\alpha_{CC}$ is the Cole-Cole relaxation time distribution parameter; when $\alpha_{CC}=0$, Eq. 1 reduces to the Debye formula. Obtained parameters are presented in Fig. 3. The Cole-Cole parameters of all presented compounds show the similar behaviour: the Cole-Cole distribution parameter $\alpha_{CC}$ strongly increases on cooling, reciprocal dielectric strength $1/\Delta \varepsilon$ exhibits a minimum at ferroelectric phase transition temperature, the soft mode frequency $\nu_r = 1/(2\pi \tau_{CC})$ slows down on cooling in the paraelectric phase. The temperature dependence of the dielectric strength $\Delta \varepsilon$ was fitted with the Curie-Weiss law (Fig. 3)

$$\Delta \varepsilon = C_{p,f}/(|(T-T_C)|),$$  \hspace{1cm} (2)

where $C_{p,f}$ is the Curie-Weiss constant and $T_C$ is the Curie-Weiss temperature. The temperature dependence of soft mode frequency $\nu_r$ in paraelectric phase was fitted

FIG. 1: Temperature dependence of the complex dielectric permittivity of CuInP$_2$(S$_{0.1}$Se$_{0.9}$)$_6$ crystals measured at several frequencies.
with the equation

$$\nu_r = A(T - T_C),$$  \hspace{1cm} (3)

where $A$ is a constant. Obtained parameters are presented in Table 1. The phase transition temperature $T_C$ in mixed crystals strongly decreases from 225 K to 185 K. For all the compounds the $C_p/C_f$ ratio is about 1.5, for the second order phase transitions this ratio must be 2, for the first order one - higher than 2. The assumption was made that in these crystals between paraelectric and ferroelectric phase an additional incommensurate phase exists [11]. However, in all mixed CuInP$_2$(Se$_x$S$_{1-x}$)$_6$ crystals with $x \leq 0.1$ no anomaly above the main (ferroelectric) phase transition was observed (Fig. 1).

Below the ferroelectric phase transition temperature the dielectric dispersion is broad and part of it appears in the low frequency region (Fig. 1). This part is caused by ferroelectric domain dynamics. Therefore, the contribution of ferroelectric domain dynamics effectively raises the dielectric strength $\Delta \varepsilon$ in the ferroelectric phase and $C_f$ constant.

---

**TABLE I: Parameters of phase transition dynamic of CuInP$_2$Se$_6$ crystals with small admixture of sulphur ($x \leq 0.1$).**

| compound                  | $C_p$, K | $C_p/C_f$ | $A$, MHz/K | $T_C$, K |
|---------------------------|----------|-----------|------------|----------|
| CuInP$_2$Se$_6$ from [9]  | 591.7    | 1.33      | 271.9      | 225      |
| CuInP$_2$(Se$_{0.96}$S$_{0.04}$)$_6$ | 309.6    | 1.43      | 193.4      | 215.7    |
| CuInP$_2$(Se$_{0.95}$S$_{0.05}$)$_6$ | 980.3    | 1.66      | 79.3       | 208.2    |
| CuInP$_2$(Se$_{0.9}$S$_{0.1}$)$_6$ | 2380.9   | 1.52      | 44.4       | 185      |

---

**FIG. 2:** Frequency dependence of the complex dielectric permittivity of CuInP$_2$(S$_{0.1}$Se$_{0.9}$)$_6$ crystals measured at several temperatures. Lines are results of Cole-Cole fits.

**FIG. 3:** Temperature dependence of the Cole-Cole parameters of complex dielectric permittivity for the CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ crystals with $x \leq 0.1$. The $\nu_r$ lines were obtained from fit with Eq. 3 and the $1/\Delta \varepsilon$ lines were obtained from Curie-Weiss fit. The data for CuInP$_2$Se$_6$ is from [9].

---

**B. Nonergodic relaxor phase in mixed CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ crystals**

Recently, the relaxor-like behaviour as an embryo of the glass state is proposed in the antiferroelectric-glass phase boundary region of DRADP crystals family [13]. Here it is showed that the growth of glass ordering is in quite a different pattern from that of the ferroelectric-glass phase boundary region. In this section we shall presented two very similar CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ compounds ($x=0.2$ and $x=0.25$), which exhibit peculiar dielectric behaviour. Each composition shows just one maximum in $\varepsilon'(T)$ and $\varepsilon''(T)$ in the range of 110 and 145 K at fre-
The dielectric permittivity $\varepsilon^*$ at various frequencies of these crystals show typical relaxor behaviour. As an example, dielectric permittivity of CuInP$_2$(Se$_{0.75}$S$_{0.25}$)$_6$ crystal is shown in Fig. 4. There is a broad peak in the real part of dielectric permittivity is observed. With frequency $T_m$ and the magnitude of the peak increases in the whole frequency range. There is a strong dielectric dispersion in a radio frequency region around and below $T_m$ at 1 kHz. The value of $T_{mm}$ (the temperature of the maximum of losses) is much lower than that of $T_m$ at the same frequency. The position of the maximum of dielectric permittivity is strongly frequency-dependent; no certain static dielectric permittivity can be obtained below and around dielectric permittivity maximum temperature $T_m$ at 1 kHz. Such behaviour can be described by the Vogel-Fulcher relationship

$$\nu = \nu_0 \exp \frac{E_f}{k(T_m - T_0)}$$  \hspace{1cm} (4)

where $k$ is the Boltzman constant, $E_f$, $\nu_0$, $T_0$ are parameters of this equations. Obtained parameters are presented in Table II.

The dielectric dispersion of CuInP$_2$(Se$_{0.75}$S$_{0.25}$)$_6$ crystals show strong temperature dependence (Fig. 5): at higher temperatures the dielectric dispersion is only in $10^7 - 10^{10}$ Hz region, on cooling the dielectric dispersion becomes broader and more asymmetric. Strongly asymmetric and very broad dielectric dispersion is observed below dielectric permittivity maximum temperature $T_m$ at 1 kHz. The Cole-Cole formula (Eq. 1) can describe such dielectric dispersion only at higher temperatures, due to predefined symmetric shape of the distribution of the relaxations times. This is clearly visible in Fig. 5, where the Cole-Cole fit is shown as dotted line. Not only Cole-Cole formula, however, other very well known predefined dielectric dispersion formulas, such as Havriliak-Negami, Cole-Davidson cannot adequate describe the di-

![FIG. 4: Temperature dependence of the complex dielectric permittivity of CuInP$_2$(S$_{0.25}$Se$_{0.75}$)$_6$ crystals measured at several frequencies.](image1)

![FIG. 5: Frequency dependence of the complex dielectric permittivity of CuInP$_2$(S$_{0.25}$Se$_{0.75}$)$_6$ crystals at several temperatures. Lines are results of fits with distributions of relaxation times (solid) and of Cole-Cole fit (dot).](image2)

| compound          | $\nu_0$, GHz | $T_{mm}$, K | $E_f/k$, K |
|-------------------|--------------|--------------|-------------|
| CuInP$_2$(Se$_{0.75}$S$_{0.25}$)$_6$ | 38.34        | 96.8         | 370         |
| CuInP$_2$(Se$_{0.4}$S$_{0.2}$)$_6$  | 10.96        | 134.5        | 150         |

![TABLE II: Parameters of the Vogel-Fulcher fit of the $T_m$ dependence of frequency for CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ crystals with 0.2 < x < 0.25.](image3)
electric dispersion of the presented crystals. More general approach must be used for determination of the broad continuous distribution function of relaxation times \( f(\tau) \) by solving a Fredholm integral equations

\[
\varepsilon'(\omega) = \varepsilon_\infty + \Delta \varepsilon \int_{-\infty}^{\infty} \frac{f(\tau)d(ln\tau)}{1 + \omega^2 \tau^2}, \tag{5a}
\]

\[
\varepsilon''(\omega) = \Delta \varepsilon \int_{-\infty}^{\infty} \frac{\omega \tau f(\tau) d(ln\tau)}{1 + \omega^2 \tau^2}. \tag{5b}
\]

with the normalization condition

\[
\int_{-\infty}^{\infty} f(\tau) d(ln\tau) = 1. \tag{6}
\]

The most general method for the solution is the Tikhonov regularization [14, 15] method. The calculated distribution of relaxation times of CuInP\(_2\)(S\(_{0.25}\)Se\(_{0.75}\))\(_6\) crystals is presented in Fig. 6. The symmetric and narrow distribution is observed only at higher temperature \( T >> T_m \) (at 1 kHz), on cooling the distributions becomes broader and more asymmetric so that below \( T_m \) (at 1 kHz) second maximum appears. Such behaviour of distribution of relaxation times have been already observed in a very well known relaxors: Pb(Mg\(_{1/3}\)Nb\(_{2/3}\))O\(_3\) (PMN) [16], Pb(Mg\(_{1/3}\)Nb\(_{2/3}\))O\(_3\)-Pb(Zn\(_{1/3}\)Nb\(_{2/3}\))O\(_3\)-Pb(SC\(_{1/2}\)Nb\(_{1/2}\))O\(_3\) (PMN-PZN-PSN) [17], Pb(Mg\(_{1/3}\)Ta\(_{2/3}\))O\(_3\) (PMT) [18] and Sr\(_{0.61}\)Ba\(_{0.38}\)Nb\(_2\)O\(_6\) (SBN) [19]. From calculated distributions of relaxation times the most probable relaxation time \( \tau_{mp} \), longest relaxation time \( \tau_{max} \) and \( \tau_{min} \) shortest relaxation time (the level 0.1 was chosen as sufficient accurate) has been obtained (Fig. 7). The shortest relaxation time \( \tau_{min} \) is about 0.1 ns for CuInP\(_2\)(S\(_{0.25}\)Se\(_{0.75}\))\(_6\) and about 0.01 ns for CuInP\(_2\)(S\(_{0.2}\)Se\(_{0.8}\))\(_6\); it increases slowly with the increase of temperature. The longest relaxation time \( \tau_{max} \) diverges according to the Vogel-Fulcher law

\[
\tau_{max} = \tau_{0max} \exp \frac{E_{max}}{k(T - T_0)}, \tag{7}
\]

where \( T_0 \) is the freezing temperature, \( E_{max} \) is the activation energy of the longest relaxation times \( \tau_{max} \) and \( \tau_{0max} \) is the longest relaxation time at very high temperatures. The obtained parameters are presented in Table III, however the most probable relaxation time \( \tau_{mp} \) diverges with good accuracy according to the Arrhenius law:

\[
\tau_{mp} = \tau_{0mp} \exp \frac{E_{mp}}{kT}, \tag{8}
\]

where \( E_{mp} \) is the activation energy of the most probable relaxation times \( \tau_{mp} \), and \( \tau_{0mp} \) is the most probable relaxation time at very high temperatures. Obtained parameters are \( \tau_{0mp} = 4.6 \times 10^{-16} \) s and \( E_{mp}/k = 2365.3 \) K for CuInP\(_2\)(S\(_{0.75}\)Se\(_{0.25}\))\(_6\) and \( \tau_{0mp} = 1.2 \times 10^{-14} \) s and \( E_{mp}/k = 1806.3 \) K for CuInP\(_2\)(S\(_{0.8}\)Se\(_{0.2}\))\(_6\). Such phenomenon can be caused by a distribution of Vogel-Fulcher temperatures \( T_0 \), where \( 0 \leq T_0 \leq T_{max} \) [20], [21]. In our case \( T_{max} \) would correspond to a Vogel-Fulcher temperature of \( \tau_{max} \) and 0 is the freezing temperature of the most probable relaxation time and all shorter relaxation times. The temperature dependence of the reciprocal static dielectric permittivity \( 1/\varepsilon(0) \) was fitted with sperical random bond random field (SRBRF)

\[
\varepsilon(0) = \frac{C_p(1 - q_{EA})}{kT - J(1 - q_{EA})}, \tag{9}
\]

where \( J \) is the mean coupling constant and \( q_{EA} \) is Edwards-Anderson order parameter, if \( q_{EA} = 0 \) then this equation becomes the Curie-Weiss law. The Edwards-Anderson order parameter \( q_{EA} \) for relaxor can be determined by equation [22]:

\[
q_{EA} = \frac{(\Delta J)}{kT}^2 (q_{EA} + \frac{\Delta f}{(\Delta J)^2})(1 - q_{EA})^2, \tag{10}
\]

where \( \Delta J \) is the variance of the coupling and \( \Delta f \) is the variance of the random fields. Obtained parameters we will discussed further together with random bonds

| compound                       | \( \tau_{0max}, \) s | \( T_0, \) K | \( E_{max}/k, \) K |
|-------------------------------|---------------------|-----------|-------------------|
| CuInP\(_2\)(S\(_{0.75}\)Se\(_{0.25}\))\(_6\) | 2.52\times10^{-8}   | 118.9     | 60.5              |
| CuInP\(_2\)(S\(_{0.8}\)Se\(_{0.2}\))\(_6\) | 1.02\times10^{-10}  | 129.4     | 211.01            |

TABLE III: Parameters of the Vogel-Fulcher fit of the temperature dependencies of the longest relaxation times \( \tau_{max} \) in CuInP\(_2\)(S\(_{0.75}\)Se\(_{0.25}\))\(_6\) crystals with \( 0.2 \leq x \leq 0.25 \).
random fields parameters of other mixed crystals. We must admit that the equations of the SRBRF model describe well static dielectric properties of the presented crystals. At sulphur concentrations between \(x=0.25\) and \(x=0.2\), morphotropic phase boundary between the para-electric phases \(\text{C2/c}\) (characteristic for \(\text{CuInP}_2\text{S}_6\)) and \(\text{P-31c}\) (characteristic for \(\text{CuInP}_2\text{Se}_6\)) or respectively ferrielectric phases \(\text{Cc}\) and \(\text{P31c}\) were suggested [11]. These results were later confirmed by X-ray and Raman investigations [23]. Therefore, the disorder in these mixed crystals is very high, and it can be reason of relaxor nature of the presented crystals.

C. Dipolar glass phase in mixed \(\text{CuInP}_2(\text{S}_x\text{Se}_{1-x})_6\) crystals

For \(\text{CuInP}_2(\text{S}_x\text{Se}_{1-x})_6\) crystals with \(x=0.4-0.9\) no anomaly in static dielectric permittivity indicating the polar phase transition can be detected down to the lowest temperatures. The dielectric spectra of these crystals are very similar. As an example, real and imaginary parts of the complex dielectric permittivity of \(\text{CuInP}_2(\text{S}_{0.8}\text{Se}_{0.2})_6\) crystals are shown in Fig. 8 as a function of temperature at several frequencies. It is easy to see a broad dispersion of the complex dielectric permittivity starting from 260 K and extending to the lowest temperatures. The maximum of the real part of dielectric permittivity shifts to higher temperatures with increase of the frequency together with the maximum of the imaginary part and manifests typical behaviour of dipolar glasses. The dielectric dispersion is symmetric of all crystals under study so that it can easily be described by the Cole-Cole formula (Fig. 9). The temperature dependence of the Cole-Cole parameters confirms typical behaviour for dipolar glasses (Fig. 10): the mean Cole-Cole relaxation time diverge according to the Vogel-Fulcher law (Eq. 7), the Cole-Cole distribution parameter \(\alpha_{CC}\) strongly increases on cooling and reaches value 0.5 below 100 K, the static dielectric permittivity temperature dependence has no expressed maxima. Usually such behaviour is analyzed in terms of the three-dimensional random-bond random-field (3D RBRF) Ising model of Pirc et al [24]. In terms of this model, the temperature dependence of static dielectric permittivity can be described with the Eq. 9. The order
parameter is defined by the two coupled self-consistent equations\[25\]

\[ P = \int_{-\infty}^{\infty} \frac{dz}{(2\pi)^{0.5}} \tanh\left(\frac{\eta}{kT}\right) \exp\left(-\frac{z^2}{2}\right), \quad (11) \]

\[ q_{EA} = \int_{-\infty}^{\infty} \frac{dz}{(2\pi)^{0.5}} \tanh\left(\frac{\eta}{kT}\right) \exp\left(-\frac{z^2}{2}\right), \quad (12) \]

where \( P \) is the polarization and

\[ \eta = (\Delta J^2 q_{EA} + \Delta f)^{0.5} z + J P. \quad (13) \]

The Equation 9 describe good enough static dielectric properties of presented dipolar glasses and obtained parameters are in good agreement with parameters obtained from Vogel-Fulcher fits, according to formula \[26\]

\[ T_0 = \Delta J/k_B. \quad (14) \]

Obtained parameters we will discuss further below together with random bonds random fields parameters of other mixed crystals.

FIG. 9: Frequency dependence of the complex dielectric permittivity of CuInP\(_2\)(S\(_{0.8}\)Se\(_{0.2}\))\(_6\) crystals at several temperatures. Lines are results of Cole-Cole fits.

D. Influence of small amount of selenium to phase transition dynamics in CuInP\(_2\)S\(_6\) crystals

Temperature dependence of the dielectric permittivity of CuInP\(_2\)S\(_6\) crystals with a small amount of selenium (\(x=0.98\)) is presented in Fig. 11. A small amount of selenium changes dielectric properties of CuInP\(_2\)S\(_6\) crystals significantly: the temperature of the main dielectric anomaly shift from about 315 to 289 K, the maximum value of the dielectric permittivity \(\varepsilon'\) significantly decreases from about 180 to 40 (at 1 MHz), at higher frequencies (from about 10 MHz) the peak of dielectric permittivity becomes frequency-dependent in CuInP\(_2\)(S\(_{0.98}\)Se\(_{0.02}\))\(_6\) crystals and a critical slowing down disappears \[6\]. An additional dielectric dispersion appears at low frequencies and at low temperatures. The CuInP\(_2\)(S\(_{0.95}\)Se\(_{0.05}\))\(_6\) crystals exhibit qualitatively similar dielectric anomaly with \(T_c\) and \(\varepsilon'_{\text{max}}\) shifting to lower values. The dielectric dispersion of presented crystals is symmetric (Fig. 12) so that it can be correctly described by the Cole-Cole formula (Eq. 1). The Cole-Cole parameters are shown in Fig. 13. The parameters of the Cole-Cole parameters for complex dielectric permittivity for the CuInP\(_2\)(S\(_x\)Se\(_{1-x}\))\(_6\) crystals with 0.4\(\leq x\leq 0.9\). The \(\tau\) lines were obtained from Vogel-Fulcher fit and the \(\varepsilon(0)\) lines were obtained from 3D RBRF model fit.

FIG. 10: Temperature dependence of the Cole-Cole parameters of complex dielectric permittivity for the CuInP\(_2\)(S\(_x\)Se\(_{1-x}\))\(_6\) crystals with 0.4\(\leq x\leq 0.9\). The \(\tau\) lines were obtained from Vogel-Fulcher fit and the \(\varepsilon(0)\) lines were obtained from 3D RBRF model fit.
FIG. 11: Temperature dependence of the complex dielectric permittivity of CuInP$_2$(S$_{0.98}$Se$_{0.02}$)$_6$ crystals measured at several frequencies.

TABLE IV: Parameters of phase transition dynamic of CuInP$_2$S$_6$ crystals with small admixture of selenium.

| compound                        | $C_p$, K | $C_p/C_f$ | $T_{Cp}$, K | $T_{Cf}$, K |
|---------------------------------|----------|-----------|-------------|-------------|
| CuInP$_2$(Se$_{0.05}$S$_{0.95}$)$_6$ | 8587.7   | 2.99      | 137.2       | 368.7       |
| CuInP$_2$(Se$_{0.02}$S$_{0.98}$)$_6$ | 1906.5   | 7.01      | 236.9       | 282.6       |

Cole distribution of relaxation $\alpha_{CC}$ strongly increase on cooling and reach 0.43 at low temperatures. The temperature dependence of the dielectric strength $\Delta\varepsilon$ was fitted with the Curie-Weiss law (Eq. 2). Obtained parameters are summarized in Table IV. The difference $T_{Cp}$-$T_{Cf}$ and ratio $C_p/C_f$ in these crystals indicate a first order, order-disorder phase transition. In ferroelectric phase the mean relaxation time $\tau_{CC}$ decreases only in a narrow temperature region and only for CuInP$_2$(S$_{0.98}$Se$_{0.02}$)$_6$, further on cooling a significant increasing of times $\tau_{CC}$ is observed. This increasing can be easily explained by the Fogel-Vulcher law (Eq. 7). These parameters are summarized in Table V. Note that all parameters of different compounds in Table V are close to each other. Such a behaviour is very similar to behaviour of betaine phosphate with a small amount of betaine phosphate [27] and in RADA [28] crystals, where a proposition that a coexistence of the ferroelectric order and dipolar glass disorder appears at low temperatures was proposed. Therefore we can conclude that mixed CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ crystals with $x \geq 0.95$ also exhibit at low temperatures a coexistence of ferroelectric and dipolar glass disorder.

E. Phase diagram

In this section we will discuss phase diagram in terms of random bonds and random fields. For ferroelectrics we assume that mean coupling constant $J/k$ is equal to $T_C$, because Curie-Weiss fit is accurate for these compounds.
and in this case Eq. 9 becomes Curie-Weiss law. Also for crystals with with $x \leq 0.1$, for the same reason we assume that $\Delta J$ and $\Delta f$ are 0. For ferroelectrics with $x \geq 0.95$ we obtained $\Delta J$ from $T_0$ (Eq. 14), we assumed that $\Delta f=0$.

In Fig. 14 we present the obtained phase diagram of mixed crystals. In the mixed CuInP$_2$(S$_x$Se$_{1-x}$)$_6$ with $x \geq 0.95$ and $x \leq 0.1$ crystals the mean coupling constant $J = (\Delta J^2 + \Delta f)^{0.5}$, therefore, they undergo ferroelectric phase transition at $J/k$. However is significant difference between phase transition dynamics of mixed crystals with $x \geq 0.95$ and $x \leq 0.1$. In mixed crystals with $x \leq 0.1$ no any coexistence of ferroelectric order and dipolar glass disorder is observed down to the lowest temperature (80 K). At temperatures below 100 K the dielectric permittivity of these compounds is very low (about 3), therefore, the phase coexistence in these compounds is unlikely. In the presence of an external electric field $E$ meaning coupling constant $J$ is expected to vary as

$$J(E) = J(0) + \alpha E^2.$$  

For mixed ferroelectric-antiferroelectric crystals is stated in [13, 29]. Really, no any evidence is indicated for polar nanoregions existence in mixed crystals. We try to fill this gap of information presenting two mixed crystals, where dielectric behaviour is very similar to very $T_C$ (Table 1).
well known relaxors PMN [30] and SBN [31] (the differences are only in \(T_m\) and \(\varepsilon''_{\text{max}}\) values). On the other hand, in phase diagram with less selenium concentration no area with nonergodic relaxor phase (Fig. 14) appears. The main cause of such phase diagram is that disorder \((\Delta f + \Delta J^2)^{0.5}\) is highest at \(x=0.2\), where mean coupling constant is also high enough. Usually, for mixed crystals is assumed that concentration dependence for \(\Delta f\) is such [24]

\[
\Delta f = 4x(1 - x)\Delta f_{\text{max}}.
\]

For \(\Delta J\) similar behaviour also was assumed. In this case if \(\Delta J\) has minimum at \(x=0.5\) the nonergodic relaxor phase can not be observed. However any existing theories can not explain \(\Delta J\) and \(\Delta f\) concentration dependence.

For compounds \(0.9 \leq x \leq 0.4\) the relation \(J \ll (\Delta f + \Delta J^2)^{0.5}\) is valid, consequently in these compounds a dipolar glass phase appears at low temperatures.

\[
\Delta f = 4x(1 - x)\Delta f_{\text{max}}.
\]

By further increasing selenium concentration the dipolar glass phase appears. In contrast to in CuInP\(_2\)S\(_6\) even a high concentration of admixture of sulphur \((x=0.1)\) has no any influence to the ferroelectric order. The same degree of ferroelectric order exist even for \(x=0.2\) and \(x=0.25\), however, in these crystals the ferroelectricity is broken into polar nano regions. The random bonds and random fields model clearly describe the asymmetry of phase diagram of mixed CuInP\(_2\)(S\(_x\)Se\(_{1-x}\))\(_6\), however this model can not identified origin of the effect. To summarize, the first experimental evidence for smearing nonergodic relaxor phase into dipolar glass phase by some doping is presented. For other relaxors the search of some admixture which transforms relaxor state into dipolar glass can also be performed.

\[\text{IV. CONCLUSIONS}\]

The ferroelectric order in CuInP\(_2\)S\(_6\) is reduced already for small \((x=0.98)\) substitution of sulphur by selenium.
(1997).

[27] J. Banys, J. Macutkevic, A. Brilingas, J. Grigas, C. Klimm, G. Voelkel, Phase Transitions, 78, 869 (2005).

[28] Z. Trybula, V. Hugo Schmidt, and John E. Drumheller, Phys. Rev. B 43, 1287 (1991).

[29] N. Korner, Ch. Pfammater, and R. Kind, Phys. Rev. Lett. 70, 1283 (1993).

[30] A. Levstik, Z. Kutnjak, C. Filipic, and R. Pirc, Phys. Rev. B 57, 11204 (1998).

[31] W. Kleemann, J. Dec, S. Miga, Th. Woike and R. Pankrath, Phys. Rev. B 65, 220101 (2002).