Rapid Communication

Novel feature of the universal power law dispersion of the ac conductivity in disordered matter

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Abstract

The ac conductivity σ_{ac} of different types of materials as a function of angular frequency ω is approximated by a 'universal' power law $\sigma_{ac} = A\omega^n$, A and n are fitting parameters. The exponent and the pre-exponential factor depend on temperature, in general. In the present Letter, we suggest an empirical law that states that the temperature evolution of $\log A$ is proportional to the temperature evolution of n. Data reported on different materials ascertain that the ratio $-\log A/n$ is constant, regardless the nature of the material and the type of conductivity.
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A large variety of disordered solids share a common frequency-dependent conductivity $\sigma(\omega)$, which is characterized by a low-frequency region of constant conductivity followed by a gradual transition at higher frequencies to a frequency-dependent conductivity. The strong dispersion of the conductivity can be approximated by an empirical power law, which has been termed by Jonscher as 'universal' one a long time ago [1]. The class of materials that show similar behavior in the ac conductivity is large, including amorphous semiconductors, organic semiconductors, ionic conducting glasses, ceramics, ionic or electronic conducting polymers, metal cluster compounds, transition metal oxides etc. The phenomenon is common to both electron or ion conducting materials. The (real part of the) dynamic conductivity σ_{ac} can be described by a power law:

$$\sigma_{ac} = A\omega^n, \tag{1}$$

where σ_{ac} is the (real part of the) ac conductivity, ω is the angular frequency of the applied electric field, A and n are fitting parameters, which, in general, are temperature dependent. Note that Eq. (1) is actually an approach to fit the experimental data in a unique manner. For example, n is often slightly frequency dependent, but such slight discrepancies do not alter the qualitative universal characteristics of the ac response of disordered media [2,3].

Various general features of the universal power law have been revealed experimentally [2–6]. Among these characteristics (which are enlisted in informative review articles [2,3]), we emphasize on the observation that, in the vast majority of disordered materials, n is less than unity at room temperature and gradually reduces to unity as temperature approaches $0 \, K^2$. n was found occasionally larger than unity at room temperature [7]. Although the temperature variation of the exponent n can be found in the literature, information about the temperature dependence of A is rather scarce. In this Letter, we propose an empirical rule indicating that, despite the temperature dependence of the parameters n and A, the ratio $-\log A/n$ is temperature independent. We have employed published data on different

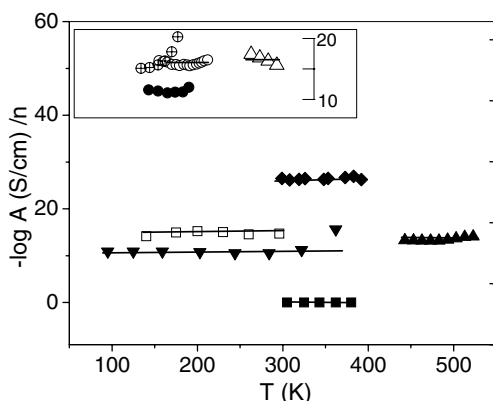* Tel.: +32 10 7276729; fax: +32 10 7661707.
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Fig. 1. The ratio $-\log A/n$ versus temperature for different type of materials: $(NH_4)_3H(SO_4)_{1.42}(SeO_4)_{0.58}$ (♦) Ref. [7]; $NaNO_3–Al_2)_3$ (▲) Ref. [9]; $10CuI–60AgI–30V_2O_5$ (△) Ref. [10]; $xAg_2S–Sb_2S_3$; $x = 70, 80$ and 85, respectively (○, ● and ⊕) Ref. [11]; $(CuI)_{0.55}–(AgSO_4)_{0.45}$ (■) Ref. [12]; $(Ag_2S)_{0.3}(AgPO_3)_{0.7}$ (□) Ref. [13]; $SeSm_{0.005}$ (▼) [14]. All data points share the same horizontal axis.
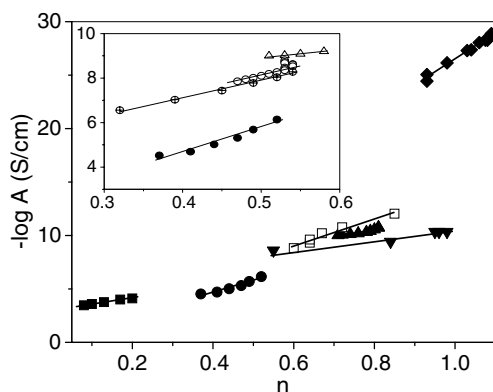

Fig. 2. $-\log A$ as a function of the exponent n of Eq. (1). Some data point sets are plotted in the inset diagram, in order to minimize overlap. The is the same as that mentioned in the caption of Fig. 1.

materials: In Fig. 1, where the ratio $-\log A/n$ is plotted as a function of temperature, for different types of materials, we see that $-\log A/n$ is near-constant. The phenomenon may be visualized better in Fig. 2 where $-\log A$ is plotted against n. The dispersion in the data points is negligible recalling that Eq. (1) is an approximate equation used to fit the experimental results; as the value of the exponent often varies slightly upon frequency, uncertainty is induced in the knowledge of A [2,3]. It is remarkable that the temperature-invariable of $-\log A/n$ holds even for the rare case of supra-linear behavior of the universal power law [7].

We believe that it is probably not coincidental that the ratio $-\log A/n$ was found independent of composition of glassy $0.3(xLi_2O \cdot (1 - x)Li_2O)0.7B_2O_3$ up to THz frequencies [8].

The above mentioned discussion leads to re-writing of the power law. By labeling $c \equiv -\log A/n$, Eq. (1) can be rewritten in the following form:

$$\log \sigma_{ac} = n(\log \omega - c). \tag{2}$$

Ac conductivity isotherms of a disordered solid vs frequency appear as straight lines in a double logarithmic plot, which pass through a common point. The slope of each line (i.e., the values of n) is controlled by temperature.

The constancy of the $-\log A/n$ ratio indicates that the temperature evolution of $-\log A$ is proportional to the temperature evolution of n, with proportionality constant depending on the specific type of material (or its microstructural network). It is still an open question which is the link between A and n with microscopic quantities and, if any, why power law applies in entirely different materials and charge transport mechanisms. The explanation (which can be grouped in the relaxation time distribution, the many-body effects on relaxation processes and random resistor-capacitor network analysis) is very much a function of the model used to simulate the specific material. At present, the unique unified knowledge hidden behind the universal power law is faint and it is hard to determine which is the meaning of $-\log A/n$. The constancy of this ratio can help to revise (re-write) the power law in a more accurate formalism.

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