Critical Behavior of the Conductivity of Si:P near the Metal-Insulator Transition

In an effort to explain the exponent puzzle, Stupp *et al.* [1] have recently claimed a crossover from the conductivity scaling exponent $\mu \sim 0.5$ for Si:P [2,3] to a larger value $\mu \sim 1.3$ as $n \rightarrow n_{c+}$ with the crossover occurring where $d\sigma/dT$ changes sign. Accurate data from a large number of samples near n_c was fit to the expression $\sigma(n,T) = \sigma_0(n)[1 + m(n)T^{1/2}]$, but the data in their Fig. 1 show $m(n)$ increasing substantially as T is reduced. The data is a better fit to $\ln\sigma(T)$ vs $T^{-1/4}$ and is strikingly similar to Si:As data [4] which, however, was interpreted as Mott variable-range-hopping (VRH) ($\ln[\sigma(T)/\sigma_0] = -(T_0/T)^{1/4}$) with T_0 scaling to zero as $n \rightarrow n_c$ with the Mott expression $T_0 \propto 1/N(E_F)\xi^3$, where $\xi = \xi_0(1 - n/n_c)^{-\nu}$. Stupp *et al.* [5] report that their 3.38, 3.45, and 3.50 samples exhibit Mott VRH, but claim those with $3.52 < n \leq 3.69$ are metallic despite their excellent fit to Mott VRH for $T > 90$ mK. Their 3.52 sample fits Mott VRH to 52 mK and yields $T_0 \sim 1$ K. Significantly, their samples with $3.55 \leq n \leq 3.69$ all show sample-dependent upward deviations from Mott VRH for $T < 90$ mK. Stupp *et al.* attribute the slight upturns for two samples (3.56 and 3.63) to thermal decoupling (TD) from the thermal reservoir, but all the samples with $n > 3.52$ in their Fig. 1 show gradual, varying (possiblly due to cracks in the Apezion N) upward deviations from Mott VRH that can plausibly be attributed to TD. The relaxation time $\tau(T)$, dominated by the Kapitza resistance, between the Cu reservoir and the Si sample becomes sufficiently long that $\omega_m\tau(T) \sim 1$ at 0.1 K ($\omega_m/2\pi = 43$ and 218 Hz [1]).

The T_0 values (from data fit for $T > 90$ mK) for Si:P vs $1 - n/n_c$ yield $3.72 < n_c < 3.74$ ($1.79 < 3\nu < 2.86$), which produces a n_c in excellent agreement with the interpretation [2–4] of $\mu \sim 0.5$. T_0 crosses over to a steeper slope for $1 - n/n_c > 0.04$ (~0.07 for Si:As), which may result from a rapidly dropping $N(E_F)$. Stupp *et al.* only consider samples with $T_0 > 4$ K as insulating, but claim those with $0.012 < T_0 < 1$ K as metallic. They claim metallic and insulating samples can be distinguished by their thermopower behavior S as $T \rightarrow 0$, but it is known that $S \rightarrow 0$ for both the metallic and Mott VRH cases as $T \rightarrow 0$. Zvyagin [6] showed $S \propto (T_0T)^{1/2}$ for Mott VRH, suggesting it will be much more difficult to distinguish metallic and insulating samples with $S(T)$ results than envisioned in [1].

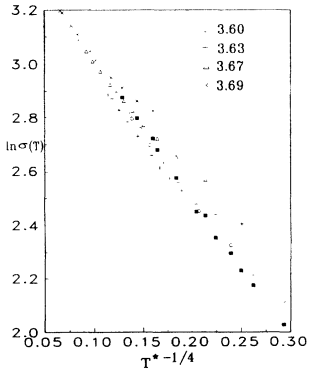

FIG. 1. $\ln\sigma$ vs $T^{*-1/4}$ for the 3.60, 3.63, 3.67, and 3.69 samples for Si:P [1], for $n_c = 3.73$, and for $3\nu = 2.27$. The black squares are not data points, but guides to the eye based on calculated values of σ for the Mott VRH parameters from the fit for $T > 90$ mK.

In their recent Reply [5] Stupp *et al.* claim their data fit a new scaling relation for metallic behavior. In fact their data fit a very simple scaling result for $n < n_c$, namely with $T^* = T/(1 - n/n_c)^{3\nu}$ and $\sigma(T) = f(T^*)$. Smooth curves obtained from data [1] for $T > 90$ mK yield the best fit with $f = \sigma_0 \exp(-T^{*-1/4})$, except for the TD effects. Figure 1 shows such a fit for all of the data for the 3.60, 3.63, 3.67, and 3.69 samples [1]. All four samples exhibit upward deviations from the expected scaling behavior below 90 mK due to the TD. The black squares (not data points) are guides to the eye based on calculated values of $\sigma(T)$ from the Mott VRH parameters for $T > 90$ mK. Figure 1 suggests a very good scaling fit to Mott VRH for $10^2 < T^* < 10^5$ K. A more complex function for T^* is required for $1 - n/n_c > 0.04$. It should also be noted that $\sigma_0 = 32.5$ S/cm (standard deviation = 1.1 S/cm) for the eight samples with $n \geq 3.52$.

In summary, the Si:P data [1] is an excellent fit to Mott VRH for $T > 90$ mK. It is suggested that TD accounts for the upward deviations from Mott VRH for $T < 90$ mK. The scaling of T_0 with $1 - n/n_c$ for *all* the samples exhibiting Mott VRH yields a n_c value in excellent agreement with the earlier determinations [2,3] for Si:P making the crossover to a larger $\mu \sim 1.3$ untenable. The so-called "rounding region" just below n_c is dominated by Mott VRH and requires ultralow temperatures [2,3]. Finally, $d\sigma/dT > 0$ for both insulating and metallic samples near n_c requiring unusual care in distinguishing between the two.

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