Reply to "Comment on 'Enhanced two-dimensional properties of the four-layered cuprate high-T_c superconductor $TlBa_2Ca_3Cu_4O_y$' "

Heon-Jung Kim,[1] Kyung-Hee Kim,[1] Sung-Ik Lee,[1] A. Iyo,[2] Y. Tanaka,[2] K. Tokiwa,[3] and T. Watanabe[3]

[1]*National Creative Research Initiative Center for Superconductivity and Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea*

[2]*National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8568, Japan*

[3]*Department of Applied Electronics, Tokyo University of Science, Noda, Chiba 278-8510, Japan*

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We present convincing arguments that support the conclusions of our original paper on $TlBa_2Ca_3Cu_4O_y$. We also reinforce the fact that $TlBa_2Ca_3Cu_4O_y$ has strong two-dimensional properties and that thermal fluctuations play an important role in the reversible magnetization down to $0.9T_c$.

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Landau and Ott have reanalyzed our magnetization data by using a scaling procedure[1] that was recently proposed by them. Based on that analysis, they claimed that the conclusion of our original paper was not correct and was not supported by the experimental data. In our paper,[2] we claimed that the $TlBa_2Ca_3Cu_4O_y$ (Tl-1234) compound had strong two-dimensional properties and exhibited a thermal fluctuation effect. We reached these conclusions based on the observations of an anomalous increase in κ with temperature near T_c, which was obtained by using the Hao-Clem analysis[3] and the scaling property within high-field scaling theory.[4] Landau and Ott insist that the increase in κ originates from insufficient accuracy in the calculation of the magnetization in the Hao-Clem model and that thermal fluctuations are negligible up to 123 K$=0.97T_c$. Furthermore, they claim that these conclusions are not restricted to Tl-1234, but generally apply to other high-T_c cuprate superconductors.[1,5–7] However these claims and conclusions of Landau and Ott are difficult to accept for the following reasons.

First, numerous data on high-T_c cuprate superconductors with values of T_c comparable to that of Tl-1234 indicate that thermal fluctuations are really important in the mixed state. For example, in $HgBa_2Ca_2Cu_3O_8$ (Hg1223) thin films, a broad vortex-liquid region was observed.[8] For a field of 5 T, a vortex-liquid region, which consists of various different regions extends from T_c down to $0.5T_c$. Among these, a flux-flow region, where thermal fluctuations are so large that vortices can even flow in a small applied current extends down to $0.8T_c$. A similar flux-flow region is expected to exist in Tl-1234 because the anisotropy ratio and the pinning properties of Tl-1234 are believed to be comparable to those of Hg-1223 thin film.

Second, the reversible magnetization was found to be strongly influenced by the thermal motion of the vortices. Bulaevskii, Ledvij, and Kogan[9] (BLK) calculated the contribution of the fluctuation of vortices to the magnetization and estimated this contribution to be comparable to the mean field magnetization down to 4–10 K below T_c. In the case of Tl-1234, that temperature range corresponds to $0.92T_c \sim 0.97T_c$. In the region where a fluctuation contribution to the magnetization is important, it reduces the absolute value of the total magnetization at a fixed temperature below mean field T_c, which is the sum of the mean field and fluctuation parts. This reduction results in the value of κ being higher than it is in the case without thermal fluctuations. Our experimental observation of an increase in κ starting at 116 K ($\sim 0.9T_c$) is consistent with this picture, and the starting temperature of that increase is in good agreement with BLK's estimated temperature of $0.92T_c$–$0.97T_c$.

Third, the above arguments are also supported by the shapes of the $M(T)$ curves near T_c, as shown in Fig. 2 of our original paper.[2] If there is no thermal fluctuation effects, mean field theories predict that the $M(T)$ curves at different fields should be parallel. This mean-field-type behavior has already been observed in the $Sr_{0.9}La_{0.1}CuO_2$ superconductor, for which the thermal fluctuation effects are weak because of its structural peculiarities.[10]

Fourth, the scaling analysis of our original data by Landau and Ott was questionable. They introduced a parameter c_0 that accounted for the temperature-dependent normal-state susceptibility. This additional parameter is, in fact, unnecessary because in our magnetization data, the paramagnetic background originated from the diamagnetic epoxy, small amount of paramagnetic impurities, and normal-state susceptibility had already been subtracted, as is usually done.[11] However, in their analysis, the value of this additional parameter was not negligible, and we believe that it played an important role in causing our magnetization to scale well in their analysis. This causes us to suspect the validity of the scaling analysis by Landau and Ott and their conclusions.

In conclusion, we have presented our critical arguments against the claims by Landau and Ott that their scaling analysis correctly described our original magnetization data and that there was no evidence for the effects of thermal fluctuations in Tl-1234. Since their scaling analysis strongly depended on an unnecessary parameter c_0, we think that they reached an incorrect conclusion. Regarding the temperature dependence of H_{c2}, we used the Werthamer-Helfand-Hohenberg (WHH) theory[12] to estimate its zero value from the data near T_c. An analysis of the reversible magnetization can produce the H_{c2} only for temperatures near T_c because of the pinning, and thus, is unsuitable for measuring the temperature dependence of H_{c2} down to low temperatures in high-T_c cuprate superconductors. Therefore, more experimental techniques are needed to verify whether or not the temperature dependence of H_{c2} deviates from the WHH theory at low temperatures.

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