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# Supporting Online Material for

## An Intrinsic Bond-Centered Electronic Glass with Unidirectional Domains in Underdoped Cuprates

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# Supporting Online Text 1

The tunneling formula of STM shown in Eq. (1) of the text is

$$I(\vec{r}, z, V) = f(\vec{r}, z) \int_0^{eV} N(\vec{r}, E)\, \mathrm{d}E. \tag{1}$$

Here $f(\vec{r}, z)$ contains the tunneling matrix elements $M(\vec{r})$ and the inverse decay length of the wave function $\kappa(\vec{r})$, and is given by

$$f(\vec{r}, z) = C|M(\vec{r})|^2 \exp\{-2\kappa(\vec{r})z\}. \tag{S1}$$

$C$ is a proportional constant, and $\kappa$ is related to the tunneling barrier height $\phi(\vec{r})$ by $\kappa(\vec{r}) = \sqrt{2m\phi(\vec{r})}/\hbar$ (*S1, S2*), where $m$ is the electron mass and $\hbar$ is the Planck constant. We get a formula for differential tunneling conductance ($\mathrm{d}I/\mathrm{d}V$) by differentiating Eq. (1),

$$g(\vec{r}, z, V) \equiv \frac{\partial I(\vec{r}, z, V)}{\partial V} = f(\vec{r}, z)eN(\vec{r}, eV). \tag{S2}$$

Eq. (S2) shows that a $\mathrm{d}I/\mathrm{d}V$ map is not proportional to an LDOS map when $f(\vec{r}, z)$ is heterogeneous. Such a situation occurs when (a) $|M(\vec{r})|^2$ and/or $\phi(\vec{r})$ are heterogeneous, and/or (b) $z$ is not constant but a function of $\vec{r}$. In actual experiments of $I(\vec{r}, z, V)$ and $g(\vec{r}, z, V)$, $z$ is usually controlled to prevent a tip from impacting the surface, and thus becomes a function of $\vec{r}$.

Let us consider these points in more detail. The adjustment of $z$ is made at each location so that a tunneling current $I_0$ is obtained at a bias voltage $V_0$. ($I_0$ and $V_0$ can be arbitrarily chosen.) This $z$ is maintained while a spectrum is taken at that location. Since this procedure is repeated at each location throughout a map, resultant spectroscopic maps are taken on a curve $z_0 \equiv z(\vec{r}; I_0, V_0)$,

$$I(\vec{r}, z_0, V) = f(\vec{r}, z_0) \int_0^{eV} N(\vec{r}, E)\, \mathrm{d}E, \tag{S3}$$

$$g(\vec{r}, z_0, V) = f(\vec{r}, z_0)eN(\vec{r}, eV). \tag{S4}$$

$z_0$ is a constant-current ($I_0$) topograph taken at $V_0$, and satisfies

$$I_0 = f(\vec{r}, z_0) \int_0^{eV_0} N(\vec{r}, E)\, \mathrm{d}E. \tag{S5}$$

Eq. (S4) means that, if $z_0$ is heterogeneous, the $\mathrm{d}I/\mathrm{d}V$ map is not proportional to the LDOS map. Moreover, Eq. (S4) indicates that knowledge of the $V_0$-dependence of the

$\mathrm{d}I/\mathrm{d}V$ maps is necessary to extract the LDOS map from the $\mathrm{d}I/\mathrm{d}V$ maps. This situation is better described in another expression for $g$ obtained from Eqs. (S4) and (S5),

$$g(\vec{r}, z_0, V) = \frac{eI_0 N(\vec{r}, eV)}{\displaystyle\int_0^{eV_0} N(\vec{r}, E)\,\mathrm{d}E}. \tag{S6}$$

Eq. (S6) shows that, if a heterogeneous $\mathrm{d}I/\mathrm{d}V$ map is observed, it is not proportional to an LDOS map unless one knows, independently of the $\mathrm{d}I/\mathrm{d}V$ map, the denominator is constant. In other words, in a system with heterogeneous LDOS, spatial variation of LDOS is not given by that of the $\mathrm{d}I/\mathrm{d}V$ map unless one chooses a special value of $V_0$ (if such exists). Eq. (S6) also indicates that a spatial variation of the denominator results in a $V$-independent contribution to the the $\mathrm{d}I/\mathrm{d}V$ map. Since the denominator of $R(\vec{r}, V_0)$ is the same as that of Eq. (S6), such a $V$-independent contribution to the $\mathrm{d}I/\mathrm{d}V$ map and a spatial pattern of $R(\vec{r}, V_0)$ could have a common physical origin.

# Supporting Online Text and Figures 2

As described in the text, an important practical advantage of the ratio map ($R$-map, $Z$-map) is that $f(\vec{r}, z)$ is cancelled out. This is true even if $z_0$ is heterogeneous. From Eqs. (S3) and (S4), we get

$$Z(\vec{r}, V) \equiv \frac{g(\vec{r}, z_0, +V)}{g(\vec{r}, z_0, -V)} = \frac{N(\vec{r}, eV)}{N(\vec{r}, eV)} \tag{S7}$$

$$R(\vec{r}, V) \equiv \frac{I(\vec{r}, z_0, +V)}{I(\vec{r}, z_0, -V)} = \frac{\displaystyle\int_0^{eV} N(\vec{r}, E)\,\mathrm{d}E}{\displaystyle\int_{-eV}^{0} N(\vec{r}, E)\,\mathrm{d}E}, \tag{S8}$$

where $z_0$ does not appear at the right side of Eqs. (S7) and (S8)

To confirm experimentally this advantage, we measured the ratio maps with several different $z_0$'s. The resultant ratio maps should be independent of $z_0$'s if $f(\vec{r}, z)$ is really cancelled out. Fig. S1 shows examples of $R$-maps taken at 150 mV with several $I_0$ and $V_0$. Obviously, images taken with different conditions are virtually identical for each material. This is true in all energies we studied. To summarize this, statistics of $R$-maps as a function of $V$ are shown in Fig. S2. For each material, the average and standard deviation are the same, independent of measurement conditions. This demonstrates that $f(\vec{r}, z)$ is actually cancelled out in the measured $R(\vec{r}, V)$ and $Z(\vec{r}, V)$.

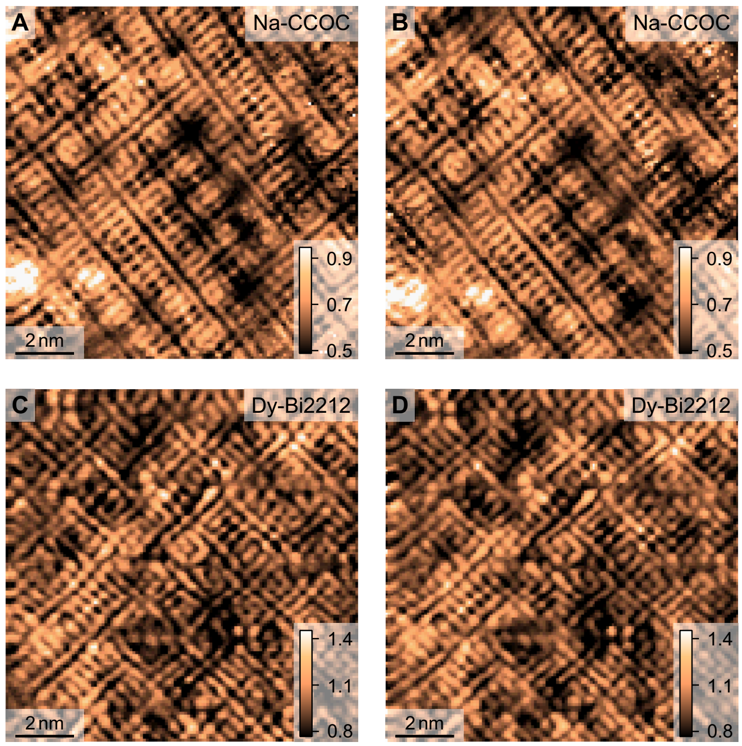


Fig. S1: 12 nm square $R$-maps taken at 0.15 V with different $I_0$ and $V_0$. (a) and (b) were measured in the same field of view except for small offset between the two measurements. Their locations were also almost identical to that of Fig. 3C. (c) and (d) were measured in a similar manner. They were equivalent to Fig. 3D but taken in a different location from that of Fig. 3D. Materials and measurement conditions are (a) Na-CCOC, $I_0 = 0.2$ nA, $V_0 = 0.6$ V, (b) Na-CCOC, $I_0 = 0.6$ nA, $V_0 =$ -0.6 V, (c) Dy-Bi2212, $I_0 = 0.2$ nA, $V_0 = 0.6$ V, and (d) Dy-Bi2212, $I_0 = 0.15$ nA, $V_0 = 0.15$ V.

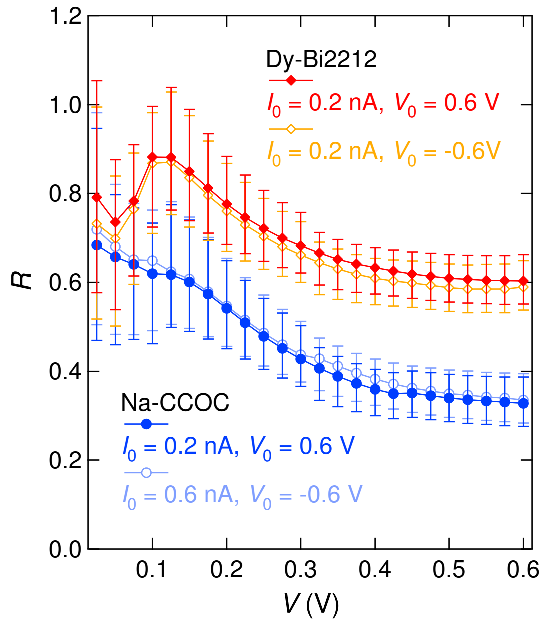


Fig. S2: Statistics of $R$-maps taken in 12 nm square field of views. Each point and error bar denote average and standard deviation, respectively.

## Supporting Online Figure 3

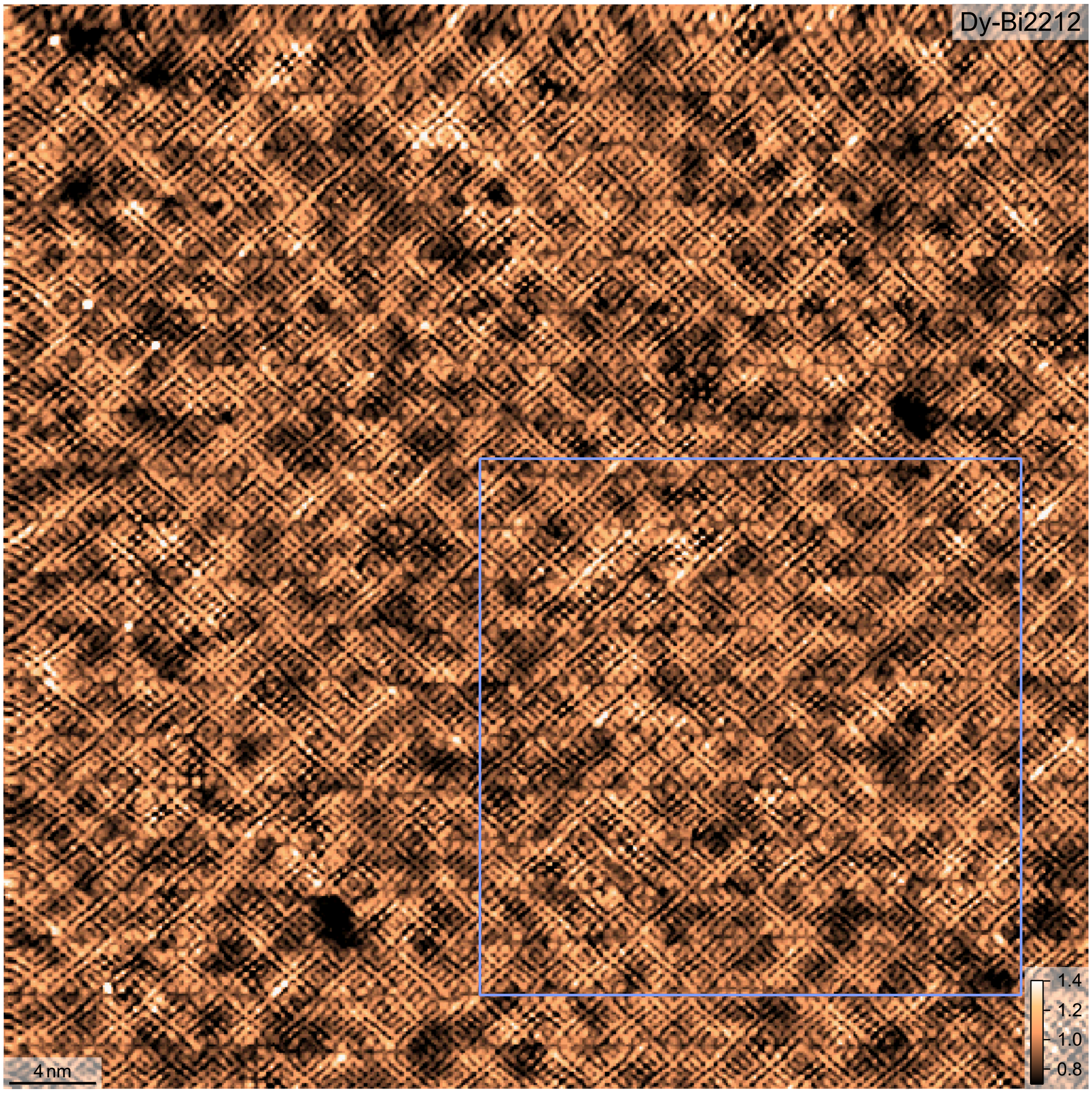


Fig. S3: A 50 nm square $R$-map taken at 0.15 V. The sample is Dy-Bi2212. The blue box shows the area of Fig. 6 of the text.

## References

[S1] J. Tersoff, D. R. Hamann, *Phys. Rev. Lett.* **50**, 1998 (1983).

[S2] J. Tersoff, D. R. Hamann, *Phys. Rev. B* **31**, 805 (1985).