

Ralph *et al.* Reply First, in Reply to point (2) of Wingreen, Altshuler, and Meir (WAM) [1], we argue that the experimental evidence shows conclusively that the signals which we described and attributed to 2-channel Kondo scattering in [2] are not due to any effect of static disorder, and, in particular, are not due to disorder-enhanced electron interactions.

(a) We have tested directly whether the signals we observe might be due to static disorder by intentionally adding disorder to our devices experimentally [2(c)]. The signals appear in roughly half of the devices made from pure Cu, but they have never been observed if more than 1% of Au is coevaporated with Cu. The signals are also absent in samples containing disorder due to electromigration of the Cu constriction or due to the adsorption of water onto the Si_3N_4 surface before metal deposition. Therefore static disorder eliminates the effect we observe, rather than enhancing it as one would have expected if the signals had been due to electron interactions.

(b) The electron-interaction mechanism proposed by WAM requires that our samples contain a region of highly disordered metal ($\ell \sim 3$ nm) with a volume at least 40–50 nm in extent [1]. We can estimate the resistance (R) of such a region by using the Drude model to calculate R for a Cu cylinder 40 nm in diameter and 40 nm long with $\ell \sim 3$ nm. The result is 7Ω . Therefore, if the bowl-shaped region of our devices were as disordered as WAM suggest, scattering from disorder in the bowl would produce the majority of the resistance in our lower- R ($<10 \Omega$) devices. If the mean free path were then to grow during annealing, so as to eliminate the electron-interaction signal, the overall R of the device would necessarily decrease by tens of percent. What we have found, in three low- R ($<10 \Omega$) devices for which we have studied the annealing, is that the resistance of two changed by less than 1% as the zero-bias signals were eliminated completely, and the resistance of the third increased by 2%. Therefore, contrary to the proposal in [1], we conclude that the amount of elastic scattering in our samples is not changed significantly during annealing, and the elimination of the zero-bias signals during annealing cannot be explained by a decrease in the magnitude of the electron-interaction effect.

(c) Two-channel Kondo scattering provides an explanation not only for the scaling properties of our data at low V and T , but also for the form of the deviations from scaling [3], and the $\log V$ and $\log T$ dependence observed [2(a)] at $V, T > T_K$. As has been argued previously [3], the electron-interaction model provides no natural explanation for the form of the deviations or the logarithmic behavior observed at higher V and T .

In response to point (1) of WAM, we believe that they are correct in pointing out that the interaction of a two-level tunneling system (TLS) with elastically scattered electron waves can act to increase the energy splitting Δ of the TLS. However, we suggest that the estimate of the average Δ in [1] is oversimplified, and the re-

sult ~ 100 K may be a considerable overestimate. As discussed by Vladar and Zawadowski [4(a)], large TLS-electron couplings are produced at low temperatures only after renormalizing smaller high- T value of the coupling to determine the effects of elastic scattering in isolation, without considering possible counteracting effects. Instead, the mechanism described by WAM should be included from the beginning in the renormalization analysis, to determine *self-consistently* how the couplings Δ and the electronic energy evolve together at low T . While the effect proposed by WAM may act to increase Δ at low T , other effects in the scaling analysis [4] act to decrease Δ strongly, and may therefore prevent any growth of Δ during renormalization and favor the formation of TLSs with $\Delta \approx 0$. We also emphasize [2(b)] that within the 2-channel Kondo picture a conductance measurement is preferentially sensitive to TLSs with small Δ , as only these TLSs will produce large V -dependent signals. Only on the order of 10 are strongly scattering TLSs necessary to explain our largest signals [2(a)]. Thus, contrary to the claims made in [1], we believe that our signals are due to a few TLSs with $\Delta \approx 0$, not *many* TLSs with a broad distribution of Δ at low T , which means that the $T^{3/2}$, $V^{3/2}$ arguments of WAM are not applicable.

In summary, we argue that the signals described in Ref. [2] are not consistent with the electron-interaction interpretation of WAM [1]. We suggest that 2-channel Kondo scattering from TLSs remains the best candidate mechanism to explain our observation.

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