Geisel and Fleischmann Reply: In their Comment Büttiker and Sánchez claim [1] (a) that our nonlinear current-voltage characteristics contradict gauge invariance (i.e., invariance under a global energy shift) and (b) that the rectifying effect disappears, if "charge neutrality" (CN), a basic self-consistent requirement, is satisfied. We will show below that (a) gauge invariance is concealed due to a simplifying convention, but can easily be restored and (b) that the rectifying effect does not disappear, if CN is required for the mesoscopic sample as a whole and not imposed for each individual channel. (The equation numbers used in the following refer to our article Ref. [2].)

(a) From the expression $I \propto \mu_L^{3/2} - \mu_R^{3/2}$ it might seem that our results are not gauge invariant indeed. This expression, however, stems from Eq. (11) [with Eq. (9)], which is gauge invariant, as only energy differences occur. Unfortunately, we did not make it clear that in Eq. (9) we have set all the potential bottoms of the channels equal to zero to simplify the following equations. On the other hand, it is easy to formulate our results in a more general form which exhibits gauge invariance explicitly. Equation (9) then reads $\varepsilon_{j,n} = (\hbar\pi n)^2/(2m^* W_j^2) + \mu_{b,j}$. Here $\mu_{b,j}$ is the bottom of the potential of channel j, which of course must follow a global energy shift. The above approximation for I then reads instead $I \propto (\mu_L - \mu_{b,j})^{3/2} - (\mu_R - \mu_{b,j})^{3/2}$, which shows the gauge invariance and is consistent with our results (as will be shown more explicitly below).

(b) The argument given in the Comment that the rectifying effect should be impeded by CN rests upon the condition, that every channel in the sample be charge neutral individually, which is a stronger assumption than necessary. Instead, following a previous article [3] by Christen and Büttiker one may require CN to hold only for the mesoscopic sample as a whole. Neglecting the spatial dependence of the self-consistent potential (as done by Büttiker and Sánchez in their Comment) then implies that the screening potential eU is constant over the entire sample. CN thus imposes only a global potential shift, which does not affect our results as we will now show. For the three-probe setup in the simplest case the screening potential is $eU = (\mu_S + \mu_D)/2 - E_F$. In the notation of (a) the potential bottoms are $\mu_b = \mu_{b,j} = eU$. The total current for the probe P in the quasiclassical case $I \propto 2(\mu_P - eU)^{3/2} - (\mu_S - eU)^{3/2} - (\mu_D - eU)^{3/2}$ is then given as $I/E_F \propto 2[\mu_P/E_F - (\mu_S + \mu_D)/(2E_F) + 1]^{3/2} - [1 + \Delta_{SD}/(2E_F)]^{3/2} - [1 - \Delta_{SD}/(2E_F)]^{3/2}$, where $\Delta_{SD} = \mu_S - \mu_D$. This expression is obviously gauge invariant, as a constant shift in all three chemical potentials cancels out. To show that this reduces to our result, let us assume for simplicity that the drain is grounded and therefore its chemical potential is fixed at the equilibrium value $\mu_D = \mu_0$. Then we can write $\mu_S = \mu_0 + \Delta\mu$ in terms of the applied bias $\Delta\mu$. Thus we find $eU = \mu_b^0 + \Delta\mu/2$, where $\mu_b^0 = \mu_0 - E_F$ are the potential bottoms in equilibrium. With these expressions we can rewrite the current as $I \propto 2(\mu_P - \mu_b^0 - \Delta\mu/2)^{3/2} - (\mu_S - \mu_b^0 - \Delta\mu/2)^{3/2} - (\mu_D - \mu_b^0 - \Delta\mu/2)^{3/2}$. Since at the probe $I = 0$, the expression corresponding to Eqs. (15) and (16) of our article becomes [with $\Delta\tilde{\mu} = \Delta\mu/(2 * E_F)$]

$$\frac{\mu_P - \mu_b^0}{E_F} = \left(\frac{1}{2}[(1 + \Delta\tilde{\mu})^{3/2} + (1 - \Delta\tilde{\mu})^{3/2}]\right)^{2/3} + \Delta\tilde{\mu}. \quad (1)$$

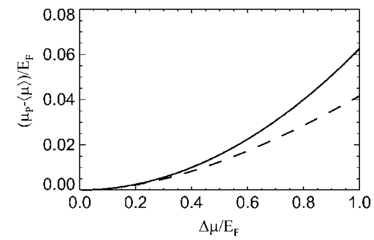

FIG. 1. Effect of a self-consistent potential on the probe potential $\mu_P - \langle\mu\rangle$ [with $\langle\mu\rangle = (\mu_S + \mu_D)/2$] as a function of the bias [solid line after Eq. (1) of this Reply] as compared to the approximation Eq. (16) of Ref. [3] (dashed line). The rectifying effect is even *enhanced* by the self-consistent potential.

In Fig. 1 we compare this result to Eq. (16) as given in our article. It clearly shows that the approximation used in our article is valid as long as $\mu_i - \mu_b^0 \approx E_F \gg \Delta\mu/2$, i.e., when the applied bias is small compared to the Fermi energy. Moreover, it shows that the rectifying effect in general is not impeded by CN, it may even be enhanced.

Büttiker and Sánchez point out the importance of a self-consistent treatment of nonlinear transport in mesoscopic conductors. We certainly agree with this, but as Christen and Büttiker state in Ref. [3], the determination of the scattering matrix as a function of the energy and the voltage shifts in the reservoirs defines a "formidable self-consistent problem." A full numerical solution of this problem for a system like the one studied experimentally by Song *et al.* [4], however desirable, still seems out of reach. While we cannot agree with the main conclusions of the Comment, it motivated us to clarify the approximations we used in the simplified and widely used transport picture we applied.

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