Full shot noise in mesoscopic tunnel barriers

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We report shot noise measurements performed in mesoscopic tunnel barriers fabricated in a GaAs/AlGaAs heterostructure. Two sets of tunnel barriers of different size are used in the study. All large size samples and some of the small size samples show a nonlinear dependence of shot noise on tunneling current due to localized states inside the barriers. Both suppression and enhancement of shot noise have been observed. Some small size barriers, however, exhibit the shot noise behavior of an ideal tunnel barrier over a wide range of barrier transmission coefficients, tunneling currents, and bias voltages.

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Shot noise, or the time dependent fluctuations of a current, measures the temporal correlations between charge transfer events through a conductor. It has proven to be a powerful tool to study transport in mesoscopic conductors. In the last decade extensive research has been carried out to understand shot noise in various mesoscopic systems.[1] Due to their unique transport properties, shot noise in these systems usually deviates from the classical poissonian value $2eI$ (or full shot noise). For example, in mesoscopic conductors both the Pauli principle and the Coulomb interaction play important roles in electron transport.[1] They introduce correlations between electron transfers and usually cause a suppression of shot noise power. A convenient quantity to measure the shot noise deviation from the Poissonian value is the Fano factor F, defined as the ratio between the actual shot noise and $2eI$. In mesoscopic conductors, both suppressed $(F<1)$ and enhanced $(F>1)$ shot noise have been predicted and demonstrated. Full shot noise, on the other hand, is rarely observed in mesoscopic systems due to the fact that it only exists in transport processes of statistically independent particle transfers, whereas in most mesoscopic conductors, transport is correlated by either Pauli principle or Coulomb interaction.

One of the ideal places to search for full shot noise is a mesoscopic tunnel barrier, characterized by a set of transmission coefficients T_n. Theory predicts that the total noise measured in such a barrier at temperature T should be[1]

$$S_I(f) = \frac{2e^2}{\pi\hbar}\left[2k_BT\sum_n T_n^2 + eV\coth\left(\frac{eV}{2k_BT}\right)\sum_n T_n(1-T_n)\right], \qquad (1)$$

where f is the frequency and V is the time averaged voltage bias.

For $V=0$, Eq. (1) simply yields the well-known thermal noise $4k_BTG$, where $G=(2e^2/h)\Sigma_n T_n$ is the barrier conductance.

For $eV \gg k_BT$, Eq. (1) reduces to the following form:

$$S_I(f) = \frac{2e^3V}{\pi\hbar}\sum_n T_n(1-T_n), \qquad (2)$$

where $I=GV$ is the time averaged current. The Fano factor in this case is

$$F = \frac{\sum_n T_n(1-T_n)}{\sum_n T_n}. \qquad (3)$$

The $(1-T_n)$ factor in Eq. (3) introduces shot noise suppression, which has been well studied in various systems.[2–4] On the other hand, if $T_n \ll 1$ for all n, $F\approx 1$. While full shot noise was observed a long time ago in macroscopic systems,[5] such as semiconductor diodes,[6] it has been demonstrated only recently for mesoscopic tunnel barriers. For example, Birk *et al.*[7] measured the shot noise in a tunnel barrier formed by a scanning tunneling microscopic (STM) tip and a metallic surface. At high bias, the measured shot noise power was $2eI$. As the bias was lowered, they observed the crossover from $2eI$ to thermal noise $4k_BTG$ as suggested by Eq. (1). To our knowledge, similar results have not been established for barriers fabricated in semiconductors. In particular, full shot noise has not been observed in mesoscopic semiconductor tunnel barriers, mainly due to the existence of localized states in these systems.

A typical semiconductor system used for forming tunnel barriers is the two-dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure. Metal gates are deposited on top of a sample and negative voltages are applied to these gates to form desired patterns. In the case of a quantum point contact (QPC), for example, the transmission coefficients can be tuned continuously by varying the gate voltages. In the region where one or more $T_n \sim 1$, shot noise suppression is expected. This has been verified experimentally.[2,3] As more negative voltages are applied, thus entering the pinch-off region where $T_n \ll 1$, one would expect that full shot noise should be observed, according to Eq. (3). However, it is well known that localized states due to impurities and potential disorder become dominant in the pinch-off regime.[8–12] In the case of a tunnel barrier, for example, a localized state weakly coupled to both source and drain contacts can cause shot noise suppression. This suppression is due to the correlation between consecutive tunneling events introduced by Coulomb interaction: as one electron tunnels onto the localized state, the on-site Coulomb repulsion prevents further tunneling of other electrons until that electron leaves the site. All theoretical work[13–16] predicted shot noise suppression in the presence of localized states. However, a recent study by

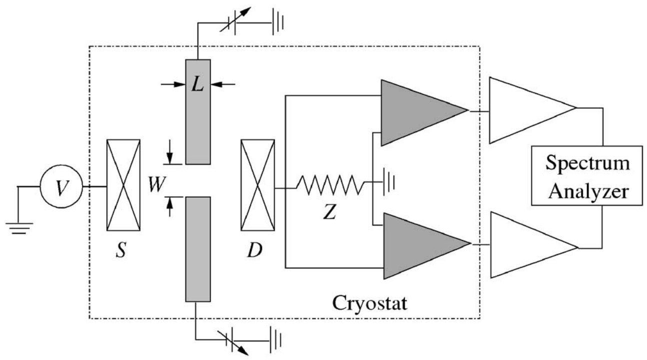

FIG. 1. A schematic of the measurement system. S and D are source and drain reservoirs. Both gates (shaded rectangles) have a width of L and are separated by a distance of W. Z is a load resistor of 10 $k\Omega$.

Safonov *et al.*[17] also found enhancement of shot noise due to interacting localized states. They investigated the shot noise of a tunnel barrier in an n-GaAs metal-semiconductor field-effect transistor (MESFET). The barrier has a size of 20 μm $\times$ 0.2 μm (0.2 μm is the dimension along the transport direction). Their work showed both suppressed and enhanced shot noise. A wide variety of noise behaviors due to localized states in mesoscopic systems have been studied both theoretically[13–16] and experimentally.[17–21] On the other hand, a clear demonstration of the shot noise behavior of an ideal tunnel barrier is still missing for semiconductor systems. In this paper, we report our observation of such a behavior in semiconductor tunnel barriers under various measurement configurations.

The samples used in this experiment were fabricated in a GaAs/AlGaAs heterostructure with an electron mobility of 6.1×10^5 cm^2/Vs and a density of 1.8×10^{15} m^{-2}. Metal gates were deposited on top of the sample about 50 nm above the 2DEG. A schematic of the gates and measurement system is given in Fig. 1. Negative voltages were applied to the two gates to form a tunnel barrier. Such a point contact structure is different from the samples used in some of the previous studies of shot noise in tunnel barriers.[17] Two sets of barriers with different gate size were used in our measurements. The larger set has a size of W=350 nm and L=200 nm, the smaller set has W=200 nm and L=50 nm. Both sets are substantially smaller than those studied by other groups.[12,17,18,21] These small samples, when pinched off to form tunnel barriers, should contain less localized states.

The samples were cooled in a top-loading dilution refrigerator with a sample cell temperature of 70 mK. The tunnel barriers were biased with either batteries or a function generator. With careful filtering, we found no difference in the measured noise between the two cases. A load resistor Z (Z=10 $k\Omega$) was in series with the tunnel barrier. The voltage fluctuations across Z was measured by two independent cryogenic amplifiers located 12 in. above sample. The signal was then further amplified at room temperature and fed into a spectrum analyzer, which calculates the cross spectrum between the two output channels. The cryogenic amplifier is home built with GaAs MESFETs. We used a circuit design similar to that described in Ref. 22. GaAs MESFETs function properly even below liquid helium temperature and are suitable for cryogenic electronics, but usually require rebiasing in order to obtain the best performance over large temperature ranges. At this low temperature, these devices exhibit negligible $1/f$ noise above 100 kHz, where the thermal noise dominates. Operating amplifiers at low temperatures also helps enhance the frequency response of the system by avoiding extra cable length, thus reducing distributive stray capacitance. Due to these two advantages, there exists a wide frequency range where the cryogenic amplifiers only contribute a small and relatively constant thermal noise background. This background noise can be easily averaged out by doing the cross-spectrum measurement mentioned above. Our measurements were done in a 20 kHz window around 220 kHz, where the $1/f$ noise of the samples is negligible for the current level used, so in all measurements the noise spectrum was white in the 20 kHz window. Depending on the precision needed, the spectrum is averaged for 1000 to 100 000 times and then integrated over the measurement window to get one data point (the noise at a given current or voltage).

At a given current I, the total voltage noise spectrum measured is

$$S_V = \left(\frac{ZR_S}{Z+R_S}\right)^2 \left(S_I + \frac{4k_BT}{Z}\right) + S_A, \tag{4}$$

where R_S is the differential resistance of the tunnel barrier, $4k_BT/Z$ is the thermal noise of the load resistor, and S_A is the residual correlation of the background noise contributed by the two amplifiers. S_I is the total noise from the tunnel barrier, including both its thermal noise and excess noise associated with current I. Both S_A and $4k_BT/Z$ have constant values, and can be determined by fitting S_V measured at zero current for a few different R_S values. In all measurements, we measured both S_V and R_S as a function of bias voltages or gate settings, thus S_I can be readily extracted using Eq. (4). For all data presented in this paper, the thermal noise of the sample $4k_BT/R_S$ is always much less than S_I, since we are only interested in the relatively high resistance tunneling regime ($R_S \gg h/e^2$). However, we still subtract this term from S_I in our data analysis to get the pure excess noise associated with the current I. All noise data in this paper was processed using the above procedure.

Figure 2(a) shows the measured noise power (squares and triangles) as a function of tunneling current for a barrier of large size at two different gate settings. For reference, the full shot noise $2eI$ is plotted as a straight line. The conductance of the barrier was monitored in the whole measurement range and had a value less than 0.02 e^2/h [see Fig. 2(b)], corresponding to a transmission coefficient less than 0.01. According to Eq. (3), full shot noise should be expected. The noise power measured at V_g=−620 mV, however, shows a nonlinear dependence on the current, exhibiting both enhancement and suppression at different current values. When the gate voltage was raised to −600 mV, the measured noise changed dramatically, becoming suppressed at all current values. These results are similar to those from other groups.[17,19,20] They usually indicate the presence of localized states in the tunnel barrier. A quantitative explanation of

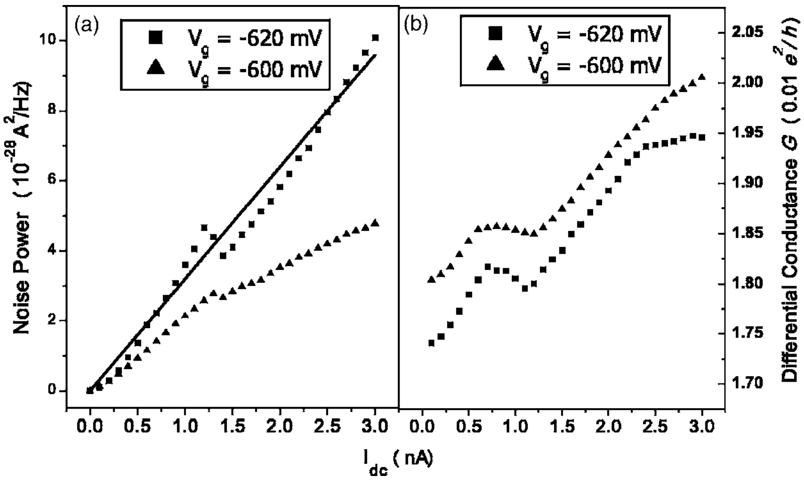

FIG. 2. (a) Shot noise as a function of tunneling current of a large size tunnel barrier at two different gating settings. The solid line represents the full shot noise $2eI$. All data are after thermal background noise subtraction. (b) Differential conductance of the same barrier measured at different currents.

the data requires information of the microscopic details (e.g., coupling between localized states and contacts) of the barrier.

Figure 3 shows the results of similar measurements on four different barriers of the smaller size. All samples tested were designed to be lithographically identical and similar voltages were applied to gates to form the tunnel barriers. Different current levels were used, ranging from a few tens pA to a few tens nA. All barriers had a conductance less than 0.02 e^2/h in the whole current range. Some barriers, as shown in Figs. 3(a) and 3(b), exhibited similar behavior as Fig. 2. For these barriers the measured noise power was a complicated function of tunneling current and sample specific. Some of them, one example given in Fig. 3(b), may have a noise power of $2eI$ in certain range but show deviations at other currents. In other barriers, however, we observed full shot noise consistently in a large range of current (e.g., 20 pA ~ 20 nA). Figures 3(c) and 3(d) are two examples. The full shot noise value $2eI$ fits the data reasonably well, so for these barriers $F=1$.

All results in Figs. 2 and 3 were reproducible when the gate voltages were removed and reapplied, as long as the sample was kept at low temperatures. After a thermal cycle to room temperature and cooled back down to low temperatures, barriers showing full shot noise usually do not change, while barriers showing deviations still show deviations but often of a different magnitude. We tested 25 tunnel barriers, including 12 large ones and 13 small ones. All large barriers showed deviations from full shot noise. Four out of 13 small barriers showed full shot noise at all current levels tested. This indicates that barriers of the large size still have a very high probability to contain localized states.

We also measured shot noise as a function of the dc bias applied across barriers. In this type of measurements, con-

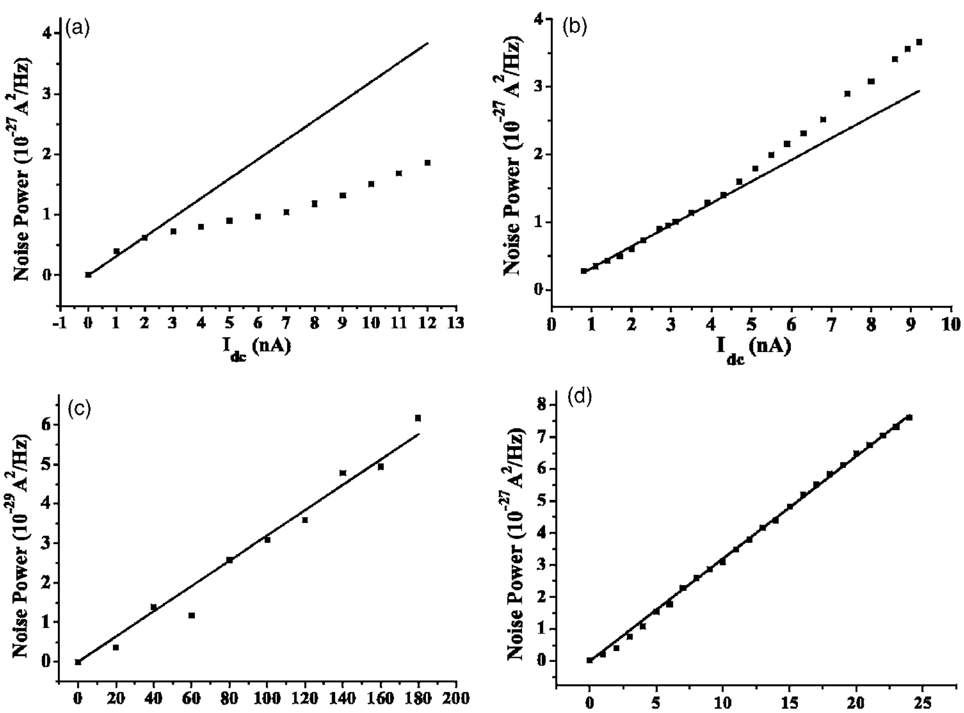

FIG. 3. Shot noise as a function of tunneling current of four small size barriers ($L=50$ nm, $W=200$ nm). Squares are measured noise power. Solid lines represent full shot noise $2eI$. All data are after thermal background noise subtraction. (a) suppressed shot noise; (b) enhanced shot noise; (c) and (d) full shot noise at low and high currents, respectively.

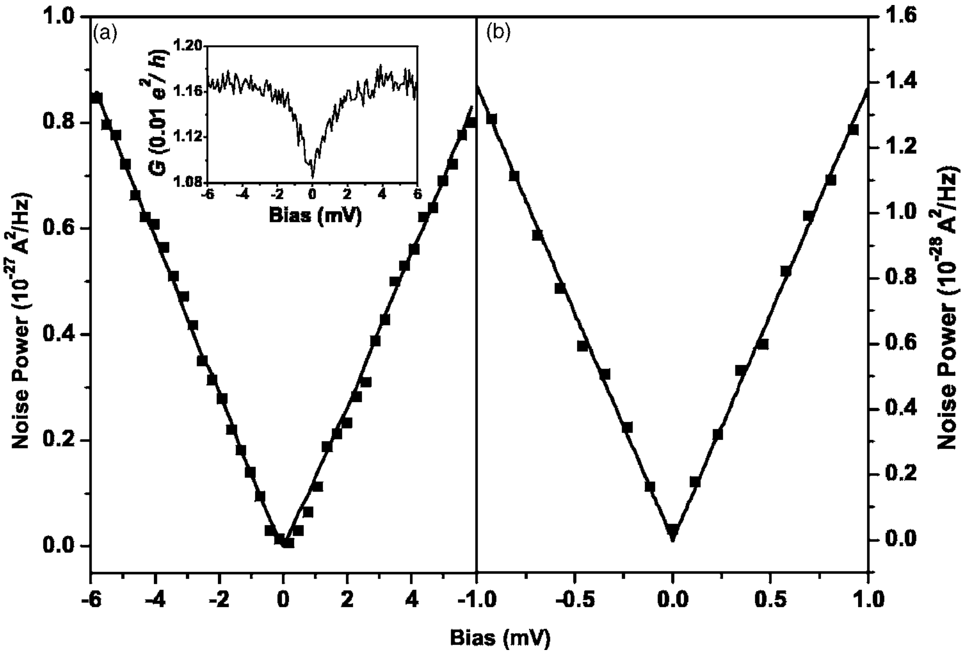

FIG. 4. Shot noise as a function of dc bias for a small size barrier in different bias range. Squares are measured shot noise power. Solid curves are for $F=1$ and are obtained by multiplying the $|I|-V$ data by $2e$. The data in (a) is more scattered because less averaging time was used. Inset to (a): differential conductance of the barrier.

ductance and shot noise of the barriers are measured simultaneously. Figure 4 shows the typical result of such measurements for another small barrier showing behavior similar to those in Figs. 3(c) and 3(d). Figures 4(a) and 4(b) were taken on the same barrier but in different bias range. The squares represent the actual measured noise power. The conductance data, namely the $|I|-V$ curve, is multiplied by $2e$ to give the full shot noise value of $F=1$, and is shown as solid lines. From the solid lines, the average conductance of the barrier can be calculated to be 0.0117 e^2/h in (a) and 0.0113 e^2/h in (b), so the barrier exhibited nearly ohmic behavior. This is further confirmed by the differential conductance measurement [the inset to Fig. 4(a)]. For such a high resistive barrier ($T_n \ll 1$), a Fano factor of 1 is expected. Our data shows very good agreement with the theory.

In addition to studying shot noise as a function of the bias voltage, we also performed spectroscopy measurements. In this type of measurements, a constant dc bias (0.5 mV for the data shown here) is applied across the barrier under test. Conductance and shot noise are measured simultaneously as a function of the voltages on the two gates forming the barrier. Figure 5 shows a typical result of this measurement on a barrier belonging to the category of Figs. 3(c) and 3(d). In this specific measurement, the voltage on the top gate (see Fig. 1) was kept constant while the voltage on the bottom gate was swept by a function generator. As that gate voltage is changed, the conductance (solid curve) of the barrier changes monotonically from 0.24 e^2/h to below 0.01 e^2/h, so the transmission coefficient T (with the assumption of only one conduction channel here so the subindex n of T_n is dropped) of the barrier changes from 0.12 to below 0.005. Correspondingly, the measured Fano factor (squares) increases from 0.88 to 1. According to Eq. (3), $F=1-T$ for the case of one conduction channel T. The dashed line in Fig. 5 represents $F=1-T$ with T deduced from the conductance data. The experimental result agrees with the theory very well in the region where the conductance is relatively high. At lower conductance, the tunneling current drops and the signal-to-noise ratio for both current and noise measurements becomes smaller, thus F exhibits more fluctuations. We note that these fluctuations do not correspond to any physical process since they are not reproducible in repetitive measurements and have a pure random nature. Overall, the measured F follows the predicted $1-T$ behavior and becomes full shot noise at very small T.

In additional measurements, we varied the voltage on the

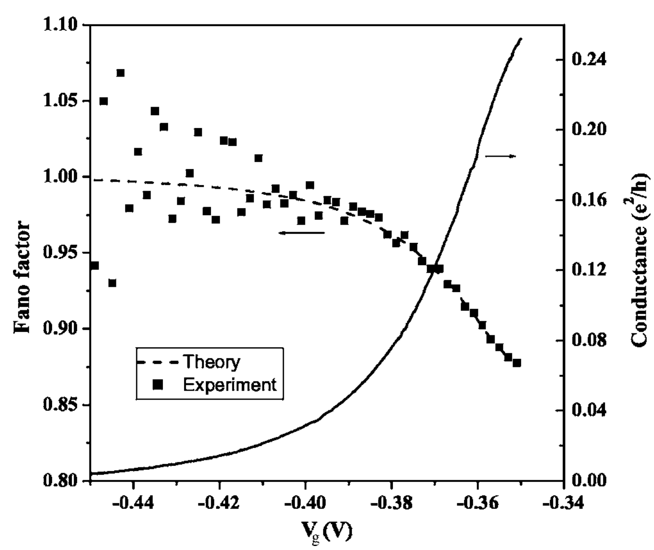

FIG. 5. Shot noise as a function of gate voltage. A dc bias of 0.5 mV is applied across the barrier. The gate voltage is varied by a function generator. Squares are measured Fano factor (measured noise power divided by $2eI$, I being the measured current). Solid curves are conductance of the barrier. The dashed curve represents the theoretical value $1-T$ of F for an ideal tunnel barrier without localized states.

top gate only or voltages on both gates and similar results were obtained. We want to point out that as the gate voltage is varied, the actual profile of the potential barrier formed by the two gates changes, so tunneling is allowed to occur at different locations between the two gates. Therefore any localized states in the vicinity of the point contact can be revealed by this type of measurement. The fact that all measurements yielded similar results as Fig. 5 confirms that these tunnel barriers do not contain any localized states.

Typically in GaAs heterostructures the localization length has been measured to be between 10 and 200 nm[18,23,24] and depends on carrier concentration and details of potential disorder. In a point contact geometry as used in this work, the electron depletion extending out from the point contact is not uniform. Thus it is impossible to model the carrier distribution or the potential fluctuations due to disorder accurately. In the highly depleted regime, the energy and position of the localized states is a random function of the details of the potential disorder and only those states accessible to the electrons will be involved in the transport processes. The average spacing between accessible localized states in our high mobility samples can be expected to be two to five times (or more) of the localization length. Thus, in our small size barriers, the probability of finding no localized states should be much larger than 10%. Experimentally we found this probability to be 31% (4 out of 13 small barriers showed ideal shot noise behavior). For our large size barriers, we expect this probability to be reduced by a factor of 7, assuming the same microscopic disorder details for each sample and ignoring the differences in the electron depletion details between the large and small samples. As a result, the probability of finding no localized states in our large barriers is about 4–5%, still nonzero but extremely small. This is consistent with our measurements.

At low temperatures, electrons can transport across an ideal tunnel barrier only through direct tunneling. For the case of very high resistance where the transmission coefficient $T \ll 1$, the correlation between tunneling events introduced by Pauli principle can be neglected, so electrons tunnel stochastically and independently, thus full shot noise is expected. Such a simple statement, however, has not been verified experimentally for mesoscopic tunnel barriers in semiconductor systems. In these systems, localized states due to impurities and potential disorder usually affect shot noise dramatically. In this work, we have presented results of shot noise measurements of mesoscopic tunnel barriers fabricated in a GaAs/AlGaAs heterostructure. Two sets of barriers of different size were used, both being substantially smaller than those studied by other groups. For the set of larger size, all barriers tested showed deviations from full shot noise. For the other set, however, two different types of behavior have been observed. Some barriers consistently exhibited full shot noise in a large range of tunneling current. For these barriers, the measurement of shot noise as a function of both bias voltage and gate voltages also yielded results that are in good agreement with the theory of shot noise of an ideal tunnel barrier without localized states. In summary, by designing very small tunnel barriers, we were able to reduce the number of localized states in each barrier. As a result, the shot noise of an ideal mesoscopic tunnel barrier was observed in semiconductor systems over a large range of measurement configurations.

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