Coulomb attractive random telegraph signal in a single-walled carbon nanotube

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The gate dependence of a Coulomb attractive random telegraph signal is observed in a single-walled carbon nanotube field effect transistor for temperatures varying from 0.32 to 24 K. The mechanism of the Coulomb attractive random telegraph signal is attributed to the carrier tunneling between the carbon nanotube and the Coulomb attractive defect. The random telegraph signal is also studied under magnetic field over an entire gate bias range and a wide temperature range. The Coulomb attractive random telegraph signal shows weak magnetic dependence, which may be due to the broadening of the Zeeman levels of the defect in the *p*-type carbon nanotube field effect transistor.

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I. INTRODUCTION

Noises and charge fluctuations are two pronounced issues in the nanodevices.[1] One kind of charge fluctuations of particular interest is random telegraph signal (RTS), which is due to the charging and discharging of individual defects. Coulomb repulsive random telegraph signals (RTSs) in the carbon nanotube field effect transistors (CNTFETs) were observed and attributed to the trapping and detrapping of the defects located inside the oxide and/or at the interface of the oxide and the single-walled carbon nanotubes (SWNTs).[2] In the previous work, it was shown that the Coulomb repulsive RTSs followed the detailed balance relationship, illustrating that the RTS emission and capture time constants were strongly affected by the energy difference between the defect level and the Fermi level of the SWNTs. A thermionic emission model was used to explain the Coulomb repulsive RTSs in the carbon nanotubes (CNTs). Furthermore, there has been work in the magneto-transport in the SWNTs. With an applied magnetic field, the transport would be dramatically modified. If the phase coherence length was smaller than the circumference of CNTs, weak localization effects, such as negative magnetoresistance and universal conductance fluctuation could be observed due to the breaking of the time-reverse symmetry.[3] In a parallel magnetic field along the SWNT direction, when the phase coherence length was much larger than the circumference, the Aharonov-Bohm oscillations were observed in CNTs due to quantum interference, i.e., the band gap and the Fermi level exhibited a periodic modulation as a function of magnetic flux passing through the nanotube.[4–6] In a strong perpendicular magnetic field, Landau levels formed and the density of states near the band edge increased.[7] Magnetic field-induced metal insulator transitions were also predicted.[8] In this paper, we first describe another kind of RTS attributed to a Coulomb attractive defect in CNTFETs. Second, the RTSs in our CNTFETs are shown to have weak magnetic field dependence, in contrast with other magnetic field studies of Coulomb repulsive RTSs in *n*-type metal oxide semiconductor field effect transistors (MOSFETs), where strong magnetic field dependence was shown.[9,10]

II. COULOMB REPULSIVE RTSs VERSUS COULOMB ATTRACTIVE RTSs

SWNTs were synthesized using a standard chemical vapor deposition (CVD) method[11] with their diameters varying from 1–3 nm and their lengths of several microns. CNTFETs used in this study are backside-gated FETs with Ti/Au as metal contacts. The random switching of current (RTS) can happen when a defect energy level aligns with the Fermi energy of the CNTFET if the defect center is located close enough to the CNT. According to the defect properties, the RTS could be classified as Coulomb repulsive or Coulomb attractive as summarized in Fig. 1. For a Coulomb repulsive RTS,[12] the defect center is neutral before trapping a carrier and becomes a positively charged center in a *p*-type FET or a negatively charged center in an *n*-type FET after capturing a carrier from the channel at a high absolute gate bias ($|V_g|$) as shown in Fig. 1(a). Thus, the current has a higher probability to stay in the low absolute source-drain current ($|I_{ds}|$) level for a larger $|V_g|$ due to the added Coulomb repulsive scattering. For a Coulomb attractive RTS, on the other hand, the defect center is positively charged in an *n*-type FET and negatively charged in a *p*-type FET before trapping a carrier and becomes neutral after capturing a carrier from the channel at a larger $|V_g|$ as shown in Fig. 1(b). Thus, the current has a higher probability to stay in the high $|I_{ds}|$level for a larger $|V_g|$ due to the absence of Coulomb attractive scattering.

Figure 2 shows the gate dependence of a CNTFET source-drain current (I_{ds}) at a temperature of 2 K. The CNTFET is a semiconducting SWNT and has a *p*-type *I*-*V* characteristic at both room and low temperatures. A RTS happens for the gate bias range from −7 to −9 V with a source-drain voltage bias (V_{ds}) of −0.5 V plotted in Fig. 2(a). The clear single-level RTS behavior indicates that the defect level is well separated from other defect states in the energy scale, and the $I_{ds}-V_g$ relation confirms that the RTS belongs to a Coulomb attractive one. The inset of Fig. 2(b) shows the time dependence of the RTS current at V_g=−7.6 V and V_{ds}=−0.5 V at T=0.32 K with 3000 measurement points at a

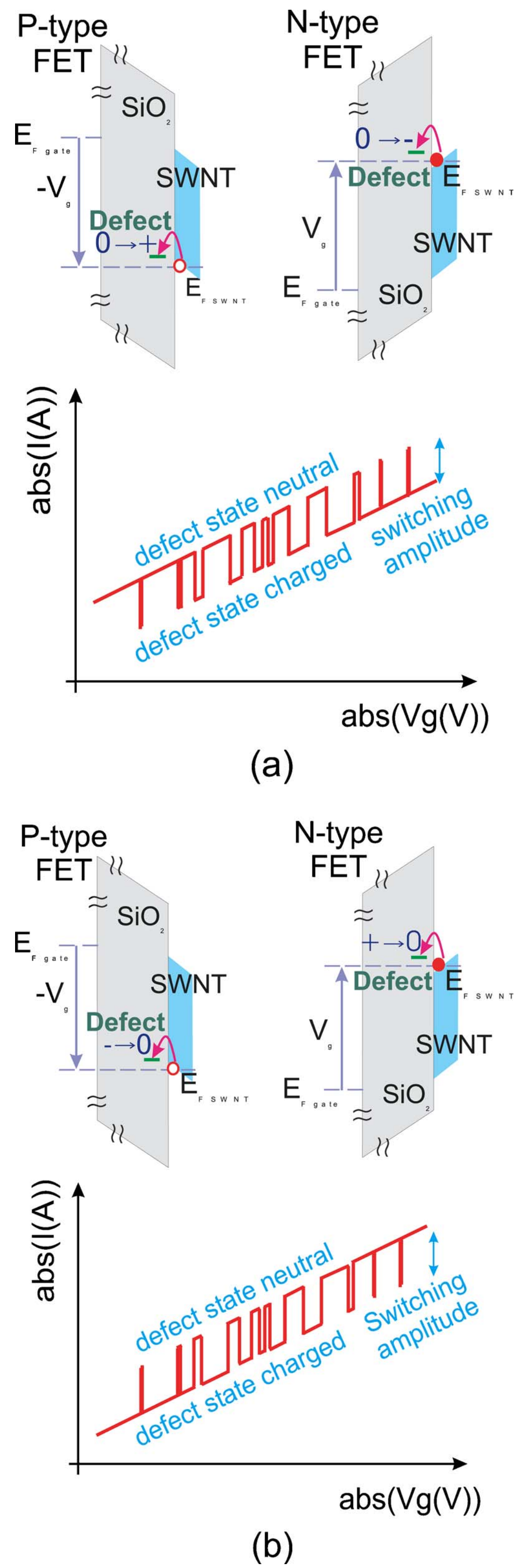

FIG. 1. (Color online) Band diagrams and schematic drawings of the corresponding I_{ds}-V_g relationship of a Coulomb repulsive RTS (a) and a Coulomb attractive RTS (b) in both a p-FET and a n-FET due to defects located near the carbon nanotubes.

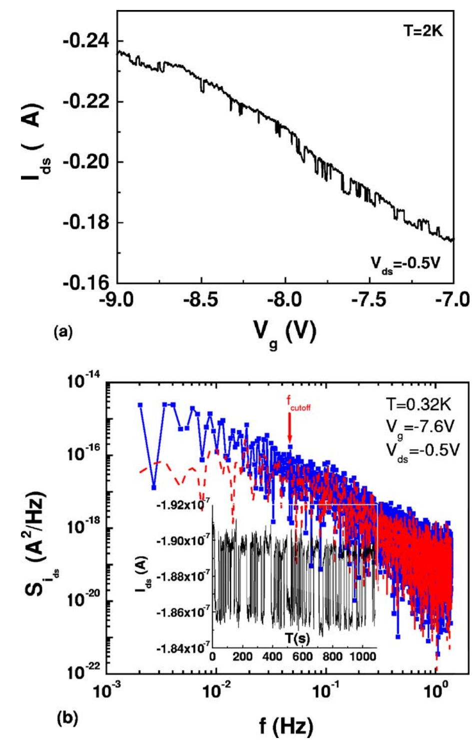

FIG. 2. (Color online) (a) Source-drain current with V_{ds}= −0.5 V measured at 2 K for the gate bias range of −7 to −9 V. (b) Noise power spectrum density of the RTS at V_g=−7.6 V obtained by a numerical method shown in the blue solid-dot line. The result deviates from an ideal Lorentzian spectrum due to a large background $1/f$ noise. The RTS power spectrum density after subtracting the background noise recovers the Lorentzian power spectrum shape with a cutoff frequency of 0.05 Hz as shown by the red/gray dashed line. The inset shows the time domain data of the RTS.

sampling rate of 0.4 s/point. From the time domain current data, the noise power spectrum density in units of A^2/Hz (shown by a blue solid-dot line) was obtained by a numerical method using MATLAB. However, the noise power spectrum density of the RTS does not show a typical Lorentzian shape,[13] and this could be due to the relatively large background $1/f$ noise. The noise spectrum density of the RTS after background subtraction is shown by a red dash line fitted well with Lorentzian spectrum with a cutoff frequency of 0.05 Hz.

Figure 3 summarizes the statistics of the emission (the average time the current is at the high absolute current level), capture (the average time the current is at the low absolute current level) time constants and their ratio as a function of gate bias measured at 0.32 K. The figure is plotted in a semilogarithmic scale. Different from the Coulomb repulsive RTS case, the relationship of the gate bias versus emission and capture time constants could only be fitted linearly for gate bias from −7.0 to −7.4 V, i.e., the emission and capture time constants do not follow an exponential dependence over the gate bias range from −7.4 to −8.4 V, suggesting that a thermionic emission model is not suitable for the Coulomb attractive RTS in the CNTFET.

Figure 4 shows emission and capture time constants at temperatures of 0.32, 1.8, 12, and 24 K. The time constants

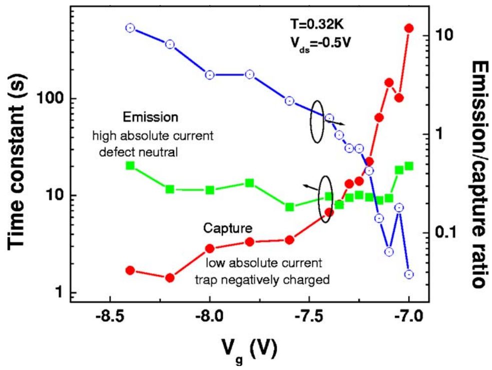

FIG. 3. (Color online) Emission and capture time constants and their ratios as a function of gate bias. For the gate range from −7.4 to −8.4 V, there is a lack of exponential dependence on gate bias.

exhibit almost no temperature dependence over almost two orders of magnitude for various gate biases, indicating a small activation energy of the RTS. The weak temperature dependence and the nonexponential gate dependence imply that the tunneling process seems to be responsible for the Coulomb attractive RTS in the CNTFET. Similar phenomena were observed for a Coulomb attractive RTS in a MOSFET.[14] For elastic tunneling processes, the emission and capture time constants follow the Fermi golden rule: $1/\tau_e = (2\pi/\hbar)D\Delta^2[1-f(E_t)]$, $1/\tau_c=(2\pi/\hbar)D\Delta^2 f(E_t)$, where D is the density of state at the Fermi level; Δ is the tunneling matrix element; $f(E_t)$ is the Fermi-Dirac distribution function for the defect level.[15,16] The gate bias versus E_t could be nonlinear in the backside-gated CNTFET. The density of state and the tunneling matrix could also change with an applied gate bias. The above facts contribute to the nonexponential gate dependence of the emission and capture time constants.

III. RTS MAGNETIC FIELD DEPENDENCE

The magnetic characteristics of the RTS in the single-walled carbon nanotube field effect transistors are investigated extensively for both Coulomb attractive and Coulomb repulsive RTS. For clarity, we only show the data obtained from the same Coulomb attractive RTS. Figure 5(a) shows the magneto- RTS behavior at the temperature of 0.32 K with the voltage bias of V_g=−7.5 V and V_{ds}=−0.5 V. The source-drain current was recorded by sweeping the magnetic field from 0 to 18 T at a ramping rate of 0.2 T/min. The sample was rotated so that the magnetic field in both perpendicular and parallel directions[17] could be applied to the sample for comparison. The emission and capture time constants show almost no magnetic dependence (the time con-

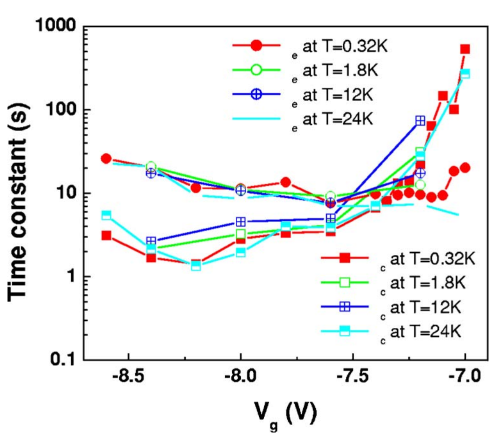

FIG. 4. (Color online) Emission and capture time constants (V_{ds}=−0.5 V) as a function of gate bias at temperatures of 0.32, 1.8, 12, and 24 K.

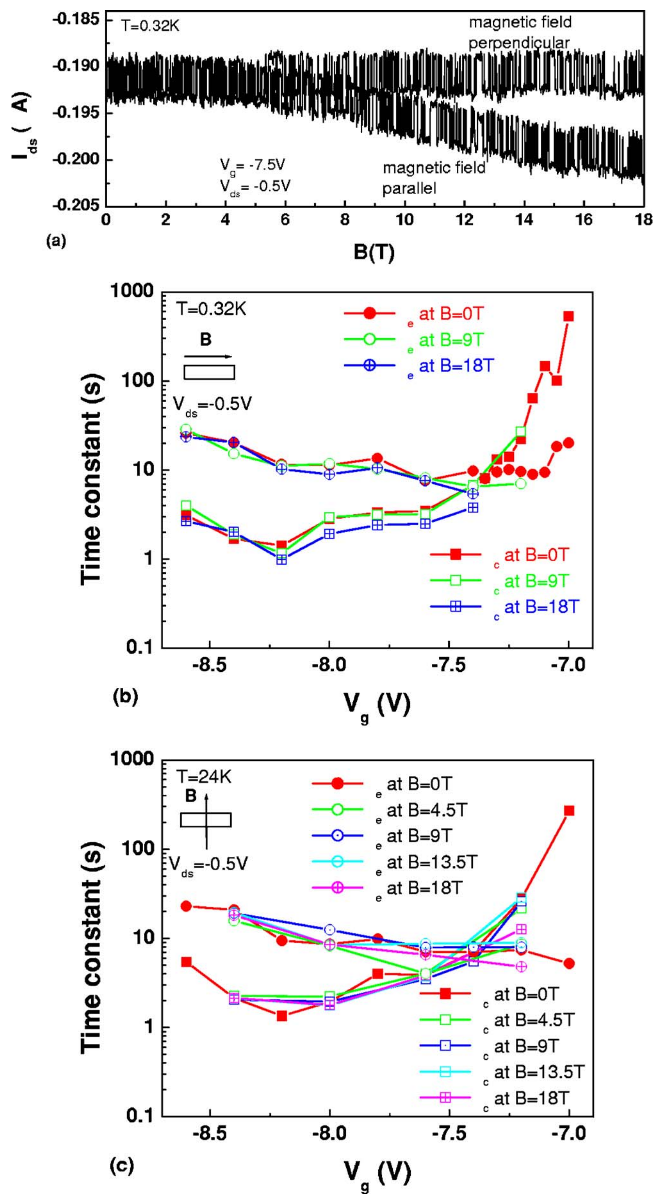

FIG. 5. (Color online) (a) The RTS with the magnetic field from 0 to 18 T in both perpendicular and parallel directions. The emission and capture time constants of the RTS show weak magnetic dependence. The applied source-drain bias is −0.5 V. 5(b) Emission and capture time constants (V_{ds}=−0.5 V) at a temperature of 0.32 K with parallel magnetic field of 0, 9, 18 T. (c) Emission / capture time constants (V_{ds}=−0.5 V) at a temperature of 24 K with the perpendicular magnetic field of 0, 4.5, 9, 13.5, and 18 T.

stant variation is less than 10%) with magnetic field up to 18 T for both the magnetic field directions over a wide temperature range from 0.32 K to 24 K. Figure 5(b) plots the statistics of the RTS time constants at the temperature of 0.32 K. The emission and capture time constants remain almost constant within the range of measurement error, indicating no longitudinal magnetic field dependence of the RTS for the entire gate bias range. Furthermore, the time constants also show no transverse magnetic field dependence for $T=24$ K as plotted in Fig. 5(c). Similar experiments were performed for more than 15 devices with Coulomb repulsive RTSs and Coulomb attractive RTSs in *p*-type CNTFETs under different gate and source-drain biases as well as at different sample temperatures. In all the cases, the absolute source-drain current increases with increasing magnetic field, and the switching amplitude of the RTSs increases roughly proportional to the increase of the source-drain current. This phenomenon becomes pronounced especially when the magnetic field is in parallel direction. However, the time constants of both Coulomb repulsive and Coulomb attractive RTSs show weak magnetic dependence.

Previously, it was demonstrated that in the *n*-type MOSFETs, the change of defect energy due to the Zeeman splitting under a magnetic field could modify the occupancy of a single defect.[9] A Coulomb repulsive defect, because of its thermionic emission mechanism, tends to follow the detailed balance relation, i.e., $\tau_c/\tau_e=g\exp[(E_t+E_z-E_f)/k_BT]$, where τ_c is the capture time constant; τ_e is the emission time constant; g is the energy level degeneracy of the trap; E_t is the defect energy at zero magnetic field; E_z is the Zeeman energy; E_f is the Fermi energy of the SWNT; T is the carrier temperature.[18] On the other hand, a Coulomb attractive defect, in the case where the Zeeman splitting model is applicable, gives the emission and capture time constants: $1/\tau_e=(2\pi/\hbar)D\Delta^2[1-f(E_t)]$, $1/\tau_c=(2\pi/\hbar)D\Delta^2 f(E_t+E_z)$, respectively. The above relations indicate that the magnetic field should be able to modulate the trap energy level so as to change the emission and capture time constant ratios for both Coulomb repulsive RTSs and Coulomb attractive RTSs. Figure 5(c) was obtained at 24 K corresponding to a thermal energy of 2 meV. The Zeeman splitting of the single defect level is 2.1 meV at a magnetic field of 18 T, and the magnetic independence could be explained due to the relatively high measurement temperature. However, the experimental results also showed little magnetic field dependence even for a temperature as low as 0.32 K (corresponding to the energy scale of 0.028 meV). In this case, even though a relatively large lateral voltage ($V_{ds}=-0.5$ V) was applied in the experiments, the carrier thermal energy remained smaller than the Zeeman energy. Moreover, other RTS magnetic field experiments performed at a small V_{ds} ($\sim$meV) also showed the weak magnetic field dependence of the time constants and their ratios, which seems to further ignore the carrier heating effect. Thus, the observed RTS does not fit the simple Zeeman splitting model. One may argue that the magnetic field can change the density of states and the Fermi level of the SWNT. If this were the case, the magnetic Fermi energy modulation should show strong anisotropic characteristics as discussed in the Introduction. However, the RTS time constants have almost no magnetic dependence for both perpendicular and parallel magnetic field directions. This may arise from the relatively long carbon nanotube with a length of 4–5 μm and the extra interface scatterings making the hole transport in the carbon nanotube diffusive. Thus, the carrier collisions in the carbon nanotube minimize the Fermi energy shift by the applied magnetic field. However, it should be noted that the hole is thermally excited into the empty defect state (for Coulomb repulsive RTS); or tunneling into the empty defect state (for Coulomb attractive RTS) during the RTS switchings. The spin relaxation for a hole is much faster than that for an electron. This is because hole angular momentum $l=1$ (in contrast to that of an electron in n type, where $l=0$); and the unique orbital component[19] (due to the cylindrical geometry of CNTs) could be conserved at least partially during the thermionic or tunneling processes. Hence, the extra spin-orbit interactions result in a fast spin relaxation time. Furthermore, the RTS defect center may come from ferromagnetic impurities like Fe used as a catalyst during the CNT synthesis process. Hence, the Zeeman level broadening due to spin relaxation could be the reason for the lack of the magnetic dependence of the random telegraph signals in CNTs. Other scattering mechanisms such as phonon and interface scattering could also contribute to the broadening of the Zeeman levels.

IV. CONCLUSIONS

In summary, the Coulomb attractive RTS was observed in a single-walled carbon nanotube field effect transistor from 0.32 to 24 K. The emission and capture time constants showed weak temperature dependence and nonexponential gate dependence, which indicated that the tunneling mechanism was responsible for the Coulomb attractive RTS in the CNTFET. Being different from the Coulomb repulsive RTS in the *n*-type MOSFETs, the RTS in the *p*-type CNT-FET showed weak magnetic dependence, which may be due to fast spin relaxation time for both the Coulomb attractive and Coulomb repulsive hole defects.

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[1] P. G. Collins, M. S. Fuhrer, and A. Zettl, Appl. Phys. Lett. **76**, 894 (2000).

[2] F. Liu, M. Bao, H. J. Kim, K. L. Wang, X. Liu, C. Li, and C. Zhou, Appl. Phys. Lett. **86**, 163102 (2005).

[3] L. Langer, V. Bayot, E. Grivei, J.-P. Issi, J. P. Heremans, C. H. Olk, L. Stockman, C. Van Haesendonck, and Y. Bruynseraede, Phys. Rev. Lett. **76**, 479 (1996).

[4] A. Bachtold, C. Strunk, J.-P. Salvetat, J.-M. Bonard, L. Forro, T. Nussbaumer, and C. Schonenberger, Nature (London) **397**, 673 (1999).

[5] S. Zaric, G. N. Ostojic, J. Kono, J. Shaver, V. C. Moore, M. S. Strano, R. H. Hauge, R. E. Smalley, and X. Wei, Science **304**, 1129 (2004).

[6] J. Cao, Q. Wang, M. Rolandi, and H. Dai, Phys. Rev. Lett. **93**, 216803 (2004).

[7] T. Ando, Semicond. Sci. Technol. **15**, R13 (2000).

[8] J. P. Lu, Phys. Rev. Lett. **74**, 1123 (1995).

[9] M. Xiao, I. Martin, and H. W. Jiang, Phys. Rev. Lett. **91**, 078301 (2003).

[10] F. A. Baron, Y. Zhang, and K. L. Wang, Appl. Phys. Lett. **82**, 3547 (2003).

[11] J. Kong, H. T. Soh, A. M. Cassell, C. F. Quate, and H. J. Dai, Nature (London) **395**, 878 (1998).

[12] F. Liu, K. L. Wang, C. Li, and C. Zhou, IEEE Transaction on Nanotechnology (to be published).

[13] A. P. van der Wel, E. A. M. Klumperink, L. K. J. Vandamme, and B. Nauta, IEEE Trans. Electron Devices **50**, 1378 (2003).

[14] M. Schulz and A. Karmann, Appl. Phys. A: Solids Surf. **52**, 104 (1991).

[15] D. H. Cobden and B. A. Muzykantskii, Phys. Rev. Lett. **75**, 4274 (1995).

[16] Y. Shi, H. M. Bu, X. L. Yuan, S. L. Gu, B. Shen, P. Han, P. Zhang, and Y. D. Zheng, Semicond. Sci. Technol. **16**, 21 (2001).

[17] However, due to the uncertainty of the SWNT direction, a component of the applied magnetic field strength may occur along the SWNT in addition to the perpendicular component.

[18] K. S. Ralls, W. J. Skocpol, L. D. Jackel, R. E. Howard, L. A. Fetter, R. W. Epworth, and D. M. Tennant, Phys. Rev. Lett. **52**, 228 (1984).

[19] E. D. Minot, Y. Yaish, V. Sazonova, and P. L. McEuen, Nature (London) **428**, 536 (2004).