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Electrically tunable magnetic fluctuations in multilayered vanadium-doped tungsten diselenide

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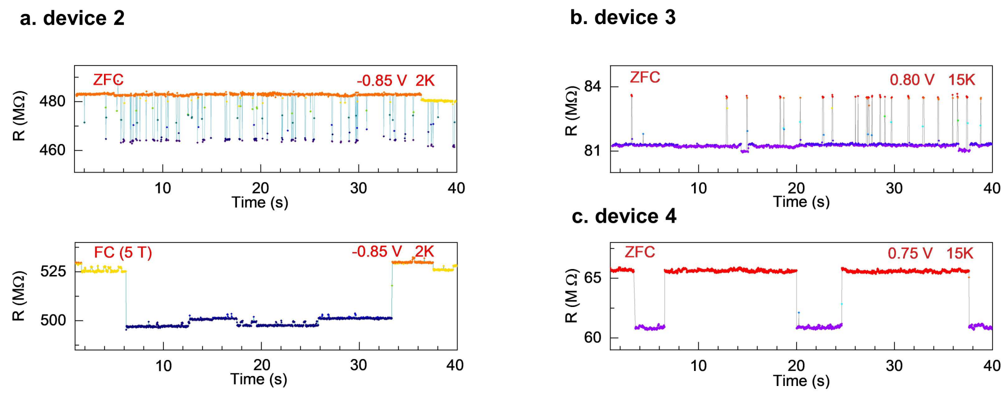
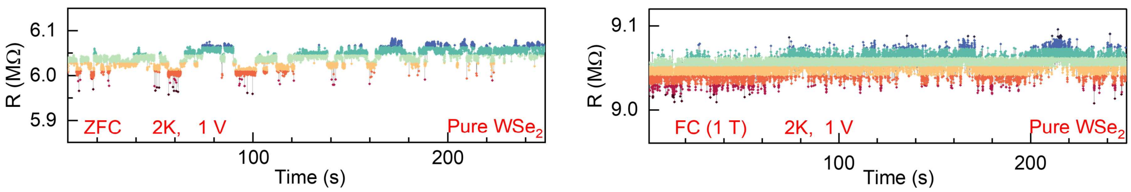
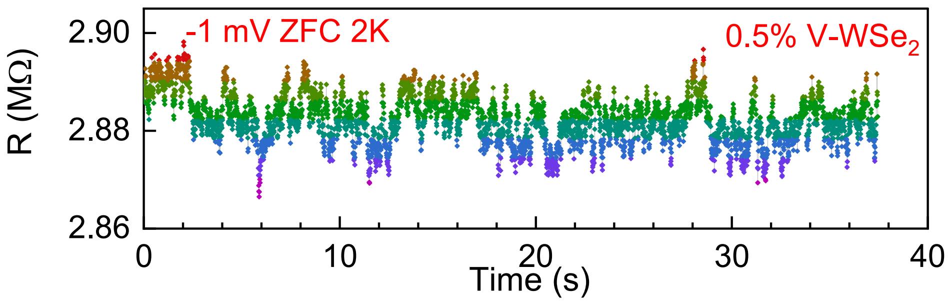
Supplementary Information



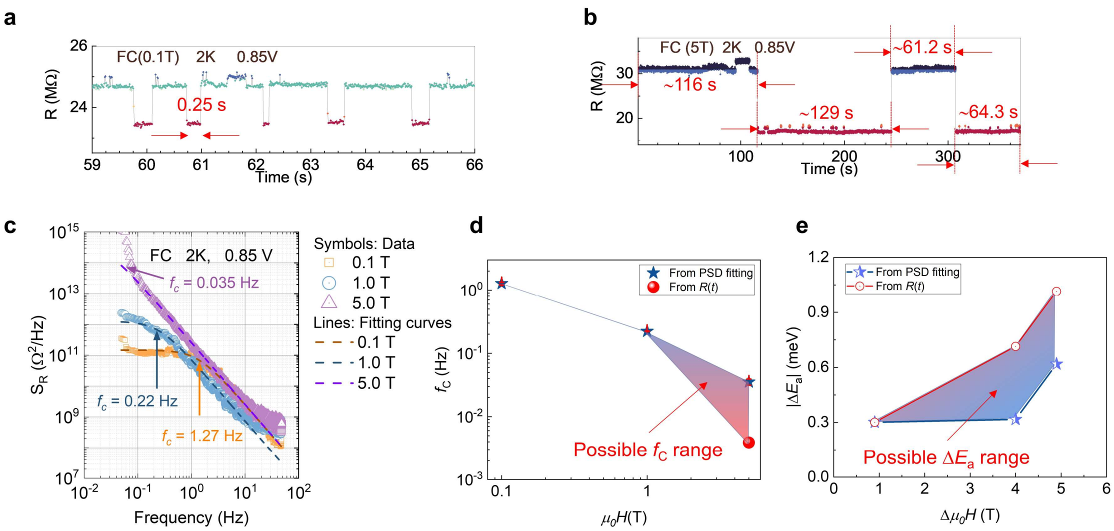
Supplementary Information Fig. 1 | Examples of RTN signals in various Gr/V-WSe_2/Gr devices. a, Time evolution of resistance change of device 2 at 0.8 V and 2 K after ZFC (top) and FC (5 T)(bottom), **b,** device 3 after ZFC at 0.8 V and 15 K, and **c**, device 4 after ZFC at 0.75 V and 15 K.



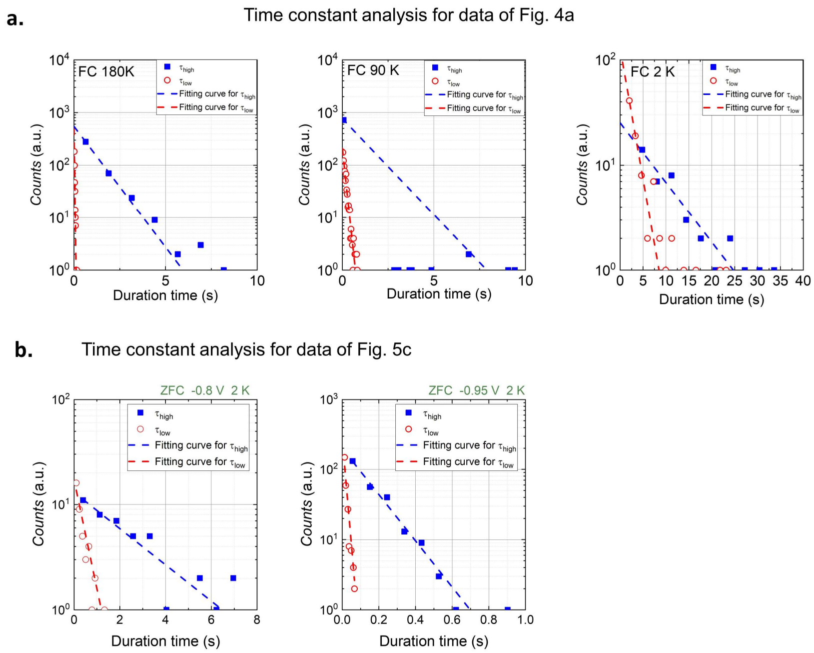
Supplementary Information Fig. 2 | Time evolution of resistance change in a Gr/WSe_2/Gr device. Random noise from pure WSe_2 after ZFC (left) and FC (right) at 2 K and 1 V.



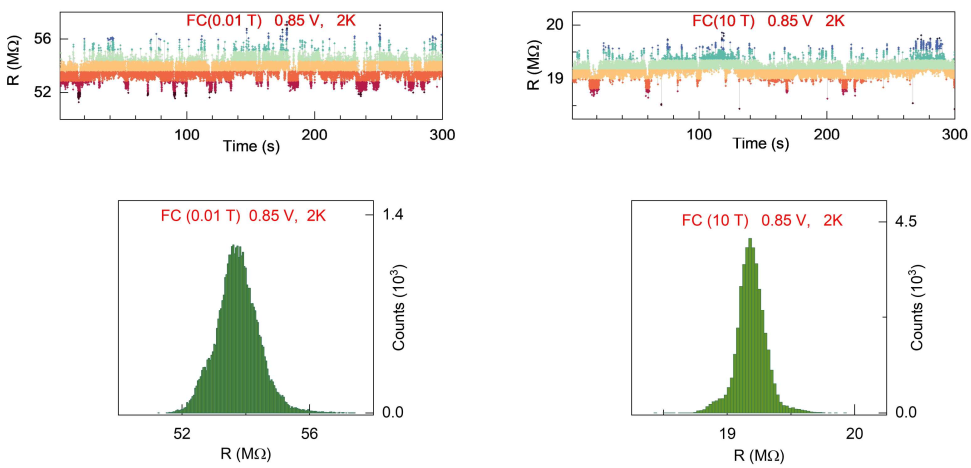
Supplementary Information Fig. 3 | Suppression of the RTN signal in high V-doping concentration (0.5% V-doped WSe_2). The data were collected after ZFC at 2 K and -1 mV.



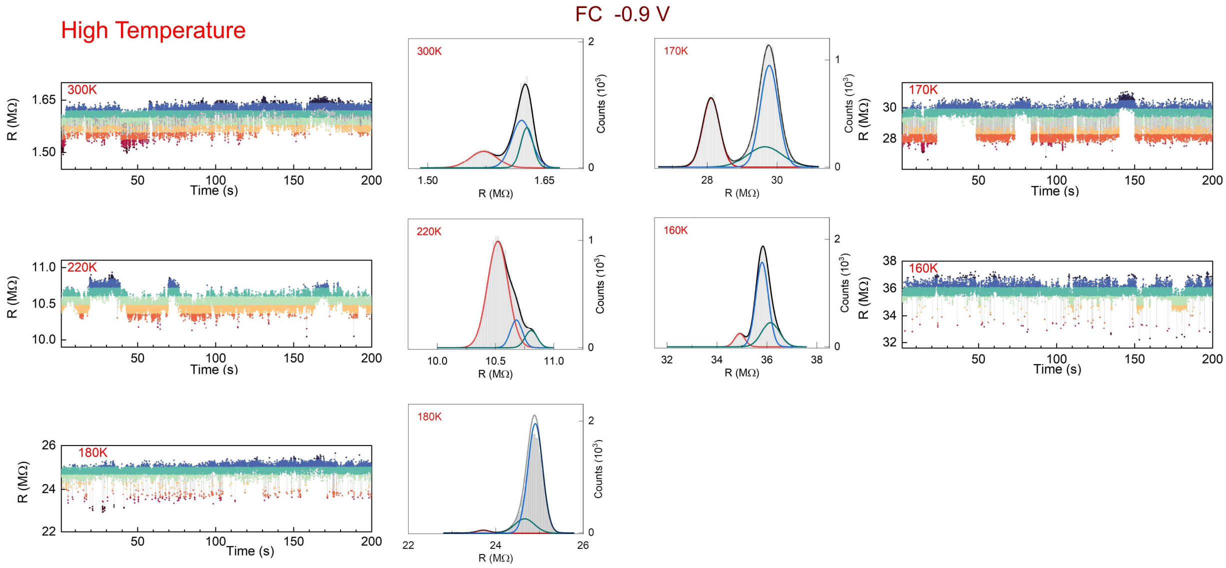
Supplementary Information Fig. 4 | Magnetic field-dependent power spectrum density (PSD) analysis of a Gr/V-WSe$_2$/Gr device. Time evolution of the resistance curve $R(t)$ at V = 0.85 V and 2 K after FC with **a**, $\mu_0 H$ = 0.1 T or **b**, $\mu_0 H$ = 5.0 T. **c,** PSD and corresponding $1/f^2$ fitting curves (dotted lines) as a function of magnetic field at V = 0.85 V and T = 2 K. **d,** Magnetic field -dependent f_c determined from PSD curve fitting and $R(t)$. After FC with high magnetic field, the number of jumps in the collected data is not large enough to accurately determine f_c, and we instead estimated this parameter from the $R(t)$ data. Error bars for f_c, standard deviation from obtained mean fc (red cross). **e**, ΔE_a in the observed magnetic field at T = 2 K based on the f_c determined by PSD and $R(t)$. Shading areas in Figures S4d-e indicate a possible range for f_C and ΔE_a, respectively. See **Supplementary Note** for details.



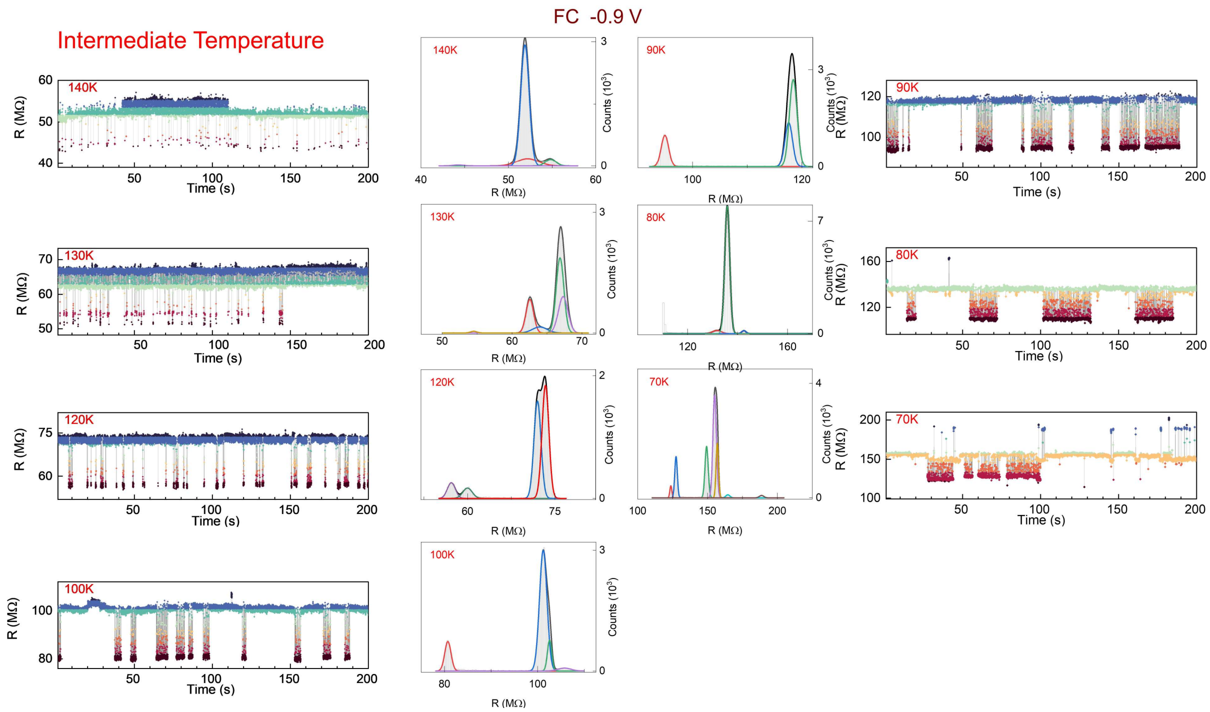
Supplementary Information Fig. 5 | Representative statistical RTN analysis for the time constant of high and low resistance levels of the RTN noise. a, temperature-dependence (Fig. 4a) and **b**, bias-dependence (Fig. 5c) time constants of RTNs.



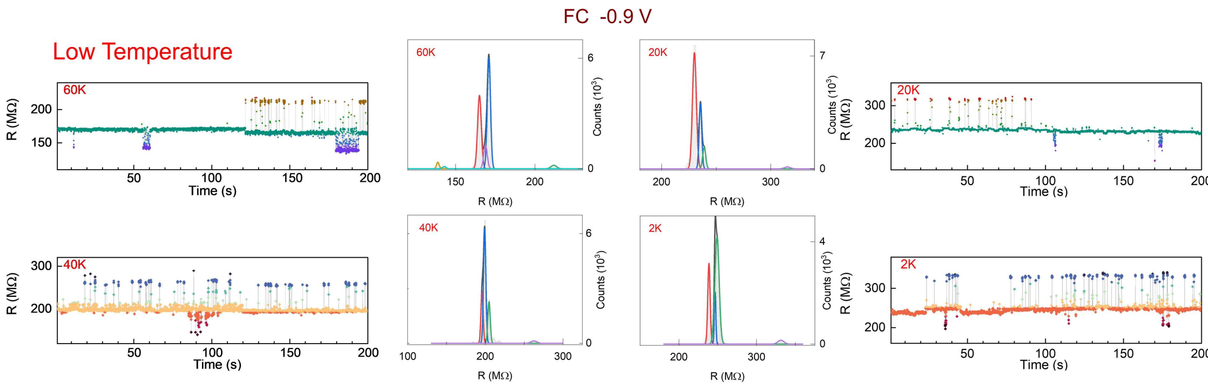
Supplementary Information Fig. 6 | Control of RTNs at low and high magnetic fields. RTNs (top) of device 1 at 2 K and 0.85 V without a magnetic field after FC with 0.01 T (left) or 10 T (right) with their corresponding single-peak histograms (bottom). No RTN signatures were observed in either condition.



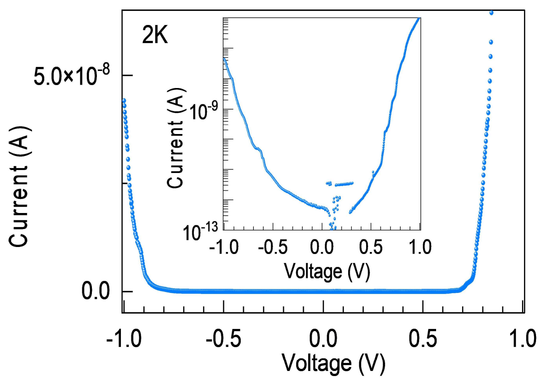
Supplementary Information Fig. 7 | Time evolution of RTNs after FC (1 T) at -0.9 V in the high-temperature region above 140 K (160–300 K) and corresponding histograms with deconvoluted curves. The histograms were well-fitted with multiple peaks. Relative resistance changes (ΔR_{norm}) were ~5%, corresponding to intralayer coupling interaction. Small $|\Delta R_{norm}s|$ in the range of ~1% also appeared.



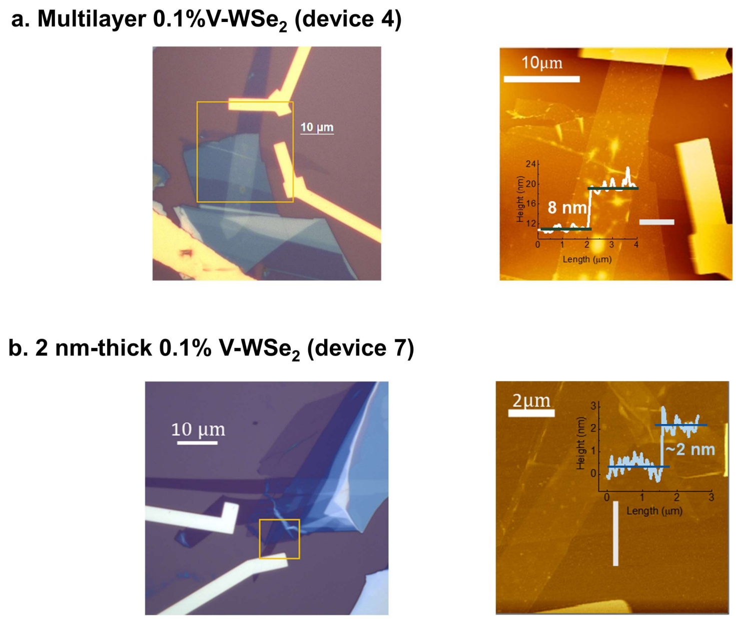
Supplementary Information Fig. 8 | Time evolution of RTNs after FC (1 T) at -0.9 V in the intermediate-temperature region (70–140 K) and corresponding histograms with deconvoluted curves. New peaks corresponding to giant $|\Delta R_{\mathrm{norm}}\mathrm{s}|$ as large as ~30% are caused by the formation of interlayer coupling.



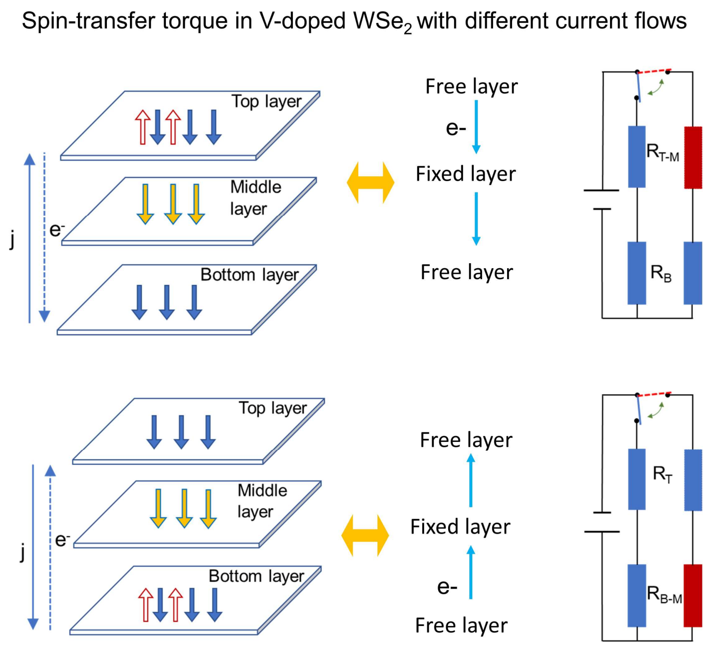
Supplementary Information Fig. 9 | Time evolution of RTNs after FC (1 T) at -0.9 V in the low-temperature region below 70 K (2–60 K) and corresponding histograms with deconvoluted curves. A new peak corresponding to giant $|\Delta R_{\mathrm{norm}}\mathrm{s}|$ as large as ~40% arises from the stable interlayer coupling.



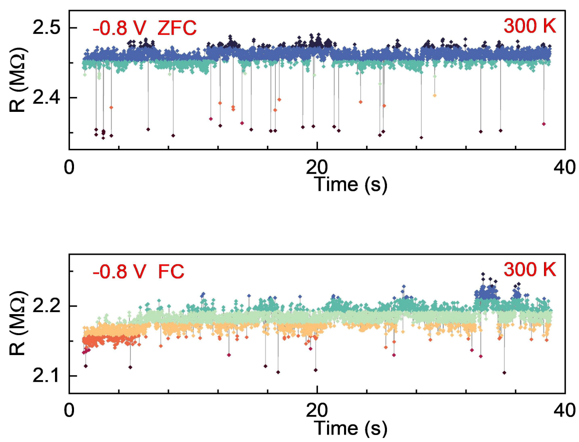
Supplementary Information Fig. 10 | The I-V characteristic of Gr/VWSe_2/Gr device 1 at 2 K in linear- and log-scales (inset) shows the Schottky junction's non-linear behavior.



Supplementary Information Fig. 11 | AFM images of Gr/V-WSe_2/Gr device: **a**, multilayer (device 4) have thickness around 5-8 nm, **b**, Thin layer has thickness around 2 nm (device 7)



Supplementary Information Fig. 12 | Trilayer model of spin-transfer torque of vertical Gr/multilayer V-WSe_2/Gr device with different current flows.



Supplementary Information Fig. 13 | RTN signal after ZFC and diminished after FC with -0.8 V at 300K. Data was measured in device 5.

Device name	Thickness of V-WSe_2 layer (nm)	Device dimensions (μm^2)
1	8	17x3
2	7	8x7
3	5	12x4
4	8	6x8
5	5	7x8
6	5	1x1
7	2	3x2

Supplementary Information Fig. 14 | Collection of the vertical 0.1% V- WSe_2 devices used in this paper.

Supplementary Note. The cut-off frequency $f_C = \frac{1}{2\pi\tau} = \frac{1}{2\pi\tau_0 exp\,(\frac{E_a}{k_B T})} = f_0\, exp\left(-\frac{E_a}{k_B T}\right)$, where τ, τ_0 (= $1/(2\pi f_0)$), E_a, k_B, and T denote the characteristic time constant, fitting constant for τ at a given temperature, activation energy, Boltzmann constant, and absolute temperature, respectively[2]. These can be determined by fitting the PSD of magneto resistance fluctuation $S_R(f) = S_0 \frac{1}{\left(1+\left(\frac{f}{f_C}\right)^2\right)} \propto 1/f^2$, where f and S_0 denote the respective frequency and noise plateau of $S_R(f)$ when $f < f_C$ (Supplementary Information Fig. S4a-c). f_C decreases with elevating magnetic fields, indicating the enhanced barrier height and suppressed transition rate between energy states 1 and 2 in the FC process (Supplementary Information Fig. S4d). The calculated τ from f_c ranging from 0.1 s to 1 s matches well to the time evaluation of RTN at $\mu_0 H$ = 0.1 T (Supplementary Information Fig. S4a). Meanwhile, the estimated τ at $\mu_0 H$ = 5.0 T is longer than 50 s, limiting an accurate determination of τ. Here, to define a realistic f_c, the effective τ ($1/\tau = 1/\tau_{state1} + 1/\tau_{state2}$ = 1.722 mHz) was considered together on the basis of the time evolution resistance (*R(t)*) data as displayed in Supplementary Information Fig. S4b, particularly when $\mu_0 H$ = 5.0 T. The Field-dependent f_c is presented in Supplementary Information Fig. S4d. In addition, the relative activation energy difference (ΔE_a) at T = 2 K was then estimated according to the following equations; $\Delta E_a = E_{a@\mu 0H=1.0\mathrm{T}} - E_{a@\mu 0H=0.1\mathrm{T}} = k_B T \cdot ln\left(\frac{f_{C@\mu 0H=0.1\mathrm{T}}}{f_{C@\mu 0H=1.0\mathrm{T}}}\right)$.

References

1. Coey, J. M. D. *Magnetism and Magnetic Materials*. *Nucl. Phys.* vol. 13 (Cambridge University Press, 2001).

2. Grasser, T. *Noise in Nanoscale Semiconductor Devices*. *Noise in Nanoscale Semiconductor Devices* (Springer International Publishing, 2020). doi:10.1007/978-3-030-37500-3.