Supporting Information

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SI Text

Device Parameter Optimization

We first investigate $\overline{T}_{\rm on}/\overline{T}_{\rm off}$ for normally incident electrons as a function of sawtooth length L and width W, assuming $L_{\rm bar}=0$ (Fig. S1). The on/off ratio is found to be maximized around $L=3W/8$. We thus choose $W=160$ nmand $L=60$ nmfor the device parameters in our studies. We then vary the length of the blade back part $L_{\rm bar}$ from 0 to 40 nm and observe that $\overline{T}_{\rm on}/\overline{T}_{\rm off}$ monotonically increases for $L_{\rm bar}\in[0,20]$ nm (Fig. S2). Therefore, $L_{\rm bar}$ is chosen to be 20 nm.

Robustness Analysis

To further check the robustness of our switching mechanism, we perform several analyses on the effects of (a) periodicity perturbation (Fig. S4), (b) potential blurring (Fig. S5), and (c) finite temperature (Fig. S6). Finally, we demonstrate our proposed mechanism is still working even under a combination of the aforementioned conditions by showing on/off behavior of a realistic device (Fig. S7).

(a) Periodicity Perturbation. We study the case when the perfect periodicity of the sawtooth potential structure is broken by including two different tooth widths of $W_{\pm}=W_0\pm\Delta W$. While changing $\Delta W/W_0$ up to 10%, the on/off ratio varies less than 5% (Fig. S4*A*). We also observe a well-defined on/off behavior in the presence of the perturbation $\Delta W/W_0=10\%$ (Fig. S4*B*).

(b) Potential Blurring. It is practically challenging to apply an electric potential that has a subnanometer sharp spatial profile due to the inclusion of an oxide layer between graphene and the gate electrode. To investigate the effect of the potential blurring, we first solve the electrostatic equations using the finite-element method and obtain the spatial profile of the carrier density $n(x,y)$ throughout the simulation region. Here, the top gate electrode is assumed to have the perfect sawtooth shape, and the space between the gate electrode and graphene is filled with an oxide layer of thickness h. For the gate oxide material, we choose HfO_2 that has the dielectric constant of 25 (1). We then convert the carrier density profile to the potential profile applied by the top gate $U(x,y)$ by using the following:

$$n(x,y)=\frac{(E_F-U(x,y))^2}{\pi v_F^2\hbar^2},$$

where $v_F$is the Fermi velocity and E_F is the Fermi energy outside the barrier. Finally, our finite-difference time domain simulator solves the time-dependent Dirac equations for 2D massless fermions with the potential profile $U(x,y)$.

The simulation results show that the on/off ratio degrades as the oxide thickness increases, i.e., as the potential gets more blurred (Fig. S5*A*). The current fabrication technique allows the deposition of HfO_2 layer with ~2-nm thickness (2), where the calculated on/off ratio is as high as 95. As shown in Fig. S5*B*, we still observe well-defined on/off behavior even when the oxide layer thickness is 5 nm.

(c) Thermal Broadening. When temperature is nonzero, the average transmittance in equilibrium ($\mu_S=\mu_D=E_F$) can be written as follows:

$$\overline{T}=\int dE\;\;T(E)\frac{df(E)}{dE}.$$

The effect of thermal broadening becomes significant when the temperature is comparable with the other energy scales such as the Fermi energy or the applied potential energy. The performance degradation turns out to be ~30% at room temperature (Fig. S6).

1. Wilk GD, Wallace RM, Anthony JM (2001) High-kappa gate dielectrics: Current status and materials properties considerations. *J Appl Phys* 89(10):5243–5275.
2. Sim JH, et al. (2005) Effects of ALD HfO_2 thickness on charge trapping and mobility. *Microelectron Eng* 80(17):218–221.

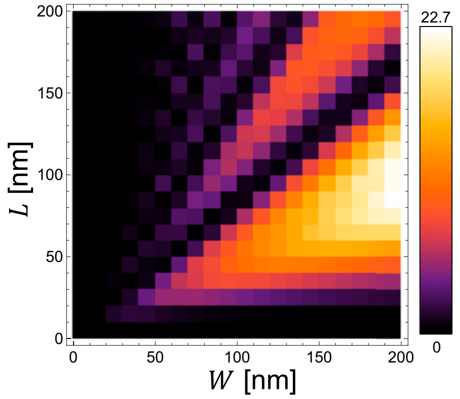

Fig. S1. Dependence of $\overline{T}_{\rm on}/\overline{T}_{\rm off}$ for normally incident electrons on the length dimensions of the sawtooth potential, L and W ($L_{\rm bar}$ is set as zero). The off state is defined as $U_0=1.1E_F=0.44$ eV. We observe that $T_{\rm on}/T_{\rm off}$ shows similar value for the same aspect ratio $a=L/W$, inferring that a is the key physical quantity determining the electron backscattering of sawtooth gate. The on/off ratio is nearly maximized when $a=3/8$. Thus, we choose our device parameters in our studies as $W=160$ nm for $L=60$ nm.

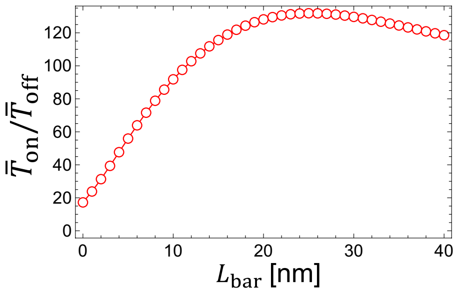

Fig. S2. Dependence of $\overline{T}_{\rm on}/\overline{T}_{\rm off}$ for normally incident electrons on the length of the blade back part of the gate electrode $L_{\rm bar}$. The device parameters are chosen as $W = 160$ nm and $L = 60$ nm. The off state is defined as $U_0 = 1.1E_F = 0.44$ eV. Due to the further reflection from the blade back part, the on/off ratio increases up to ~130 until $L_{\rm bar} \sim 20$ nm, and then slowly degrades. Thus, we choose $L_{\rm bar} = 20$ nm in our studies.

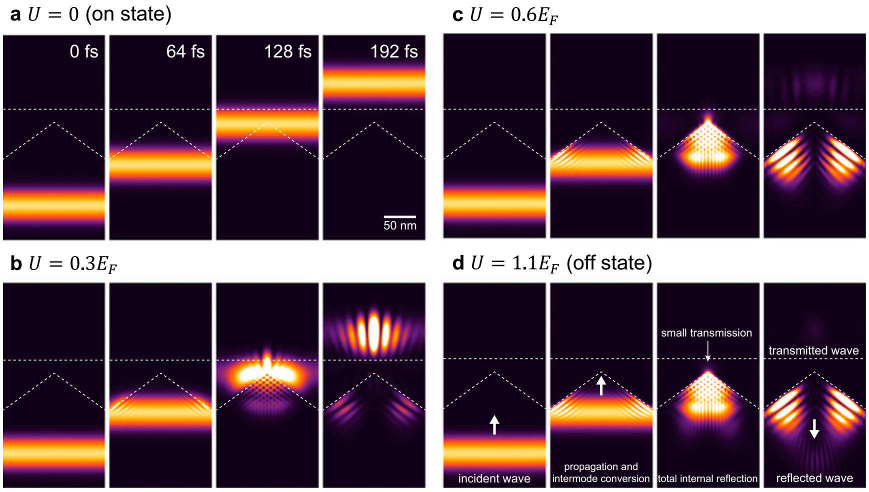

Fig. S3. Snapshots of an electron probability density profile when the device is at (*A*) $U = 0$ (on state), (*B*) $U = 0.3E_F$, (*C*) $U = 0.6E_F$, and (*D*) $U = 1.1E_F$ (off state) (to track the position of electron, the packet is localized in the *y* direction with the size of $\Delta_y = 20$ nm). The device parameters are chosen as $L = 60$ nm, $W = 160$ nm, $L_{\rm bar} = 20$ nm, and $E_F = 0.4$ eV. The electron is introduced from the bottom boundary at $t = 0$. The freestanding electron travels, and then it is coupled to the guided modes in the valley region of the gate potential ($t = 64$ fs). It further propagates along the *y* direction, and the potential barrier induce by the top gate either transmits or reflects the electron wave depending on their heights (t = 128–196 fs).

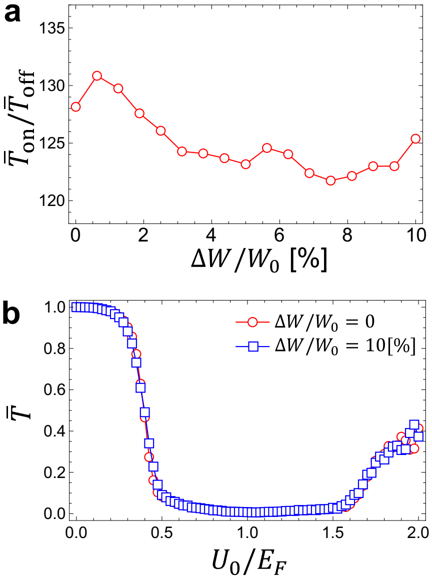

Fig. S4. (*A*) $\overline{T}_{\mathrm{on}}/\overline{T}_{\mathrm{off}}$ for normally incident electrons when the perfect periodicity of the sawteeth potential structure is broken by including two different tooth widths of $W_{\pm} = W_0 \pm \Delta W$. The device parameters are chosen as $W_0 = 160$ nm, $L = 60$ nm, and $L_{\mathrm{bar}} = 20$ nm. The off state is defined as $U_0 = 1.1E_F = 0.44$ eV. While changing $\Delta W/W_0$ up to 10%, the on/off ratio is marginally varied. (*B*) When the periodicity of the sawtooth potential is perfect (red circles) and perturbed by 10% (blue squares), we observe well-defined on/off behaviors. This shows the robustness of our gating mechanism under small perturbations on the sawtooth periodicity.

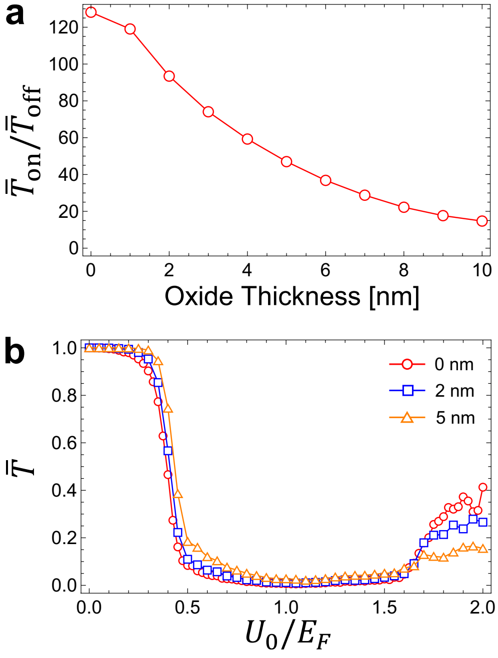

Fig. S5. (*A*) $\overline{T}_{\mathrm{on}}/\overline{T}_{\mathrm{off}}$ for normally incident electrons when the sawtooth gate potential is blurred due to the finite thickness of the HfO_2 oxide layer with relative permittivity of 25. The device parameters are chosen as $W = 160$ nm, $L = 60$ nm, and $L_{\mathrm{bar}} = 20$ nm. The off state is defined as $U_0 = 1.1E_F = 0.44$ eV. The top gate potential profile for given oxide thickness is calculated by solving Poisson equation using finite-element method. As the oxide thickness increases, i.e., as the potential is blurred, the on/off ratio degrades. The current fabrication technique allows the deposition of HfO_2 layer with ~2 nm, where the calculated on/off ratio is as high as 95. (*B*) When the HfO_2 oxide thickness is finite (2-nm case is shown with blue squares, 5-nm case is shown with orange triangles, and the case without oxide layer is shown with red circles), we still observe well-defined on/off behaviors. These results suggest that the development of high-*K* dielectric materials and precise fabrication will be of importance to minimize the performance degradation.

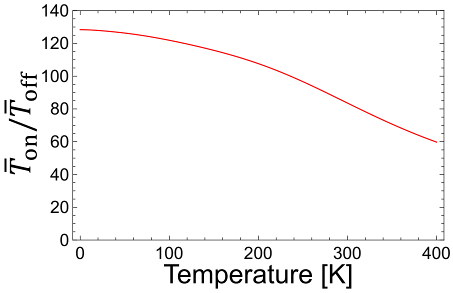

Fig. S6. Temperature dependence of $\bar{T}_{\rm on}/\bar{T}_{\rm off}$ for normally incident electrons. The device parameters are chosen as $W = 160$ nm, $L = 60$ nm, and $L_{\rm bar} = 20$ nm. The off state is defined as $U_0 = 1.1E_F = 0.44$ eV. At room temperature, $\bar{T}_{\rm on}/\bar{T}_{\rm off}$ is as high as 85, which is still almost 2 orders of magnitude increase compared with the bar-shaped gate.

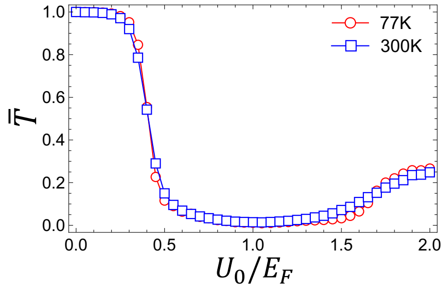

Fig. S7. A realistic behavior of the average transmittance $\bar{T}$ as a function of U_0. The device parameters are chosen as $W = 160$ nm, $L = 60$ nm, and $L_{\rm bar} = 20$ nm. The thickness of the HfO_2 oxide layer is assumed to be 2 nm. $\bar{T}_{\rm on}/\bar{T}_{\rm off}$ is as high as 95 at zero temperature, 92 at 77 K (red circles), and 65 at room temperature (blue squares). The off state is defined as $U_0 = 1.1E_F = 0.44$ eV.