Generation of a Single-Electron Gaussian Wave Packet Using Dynamical Quantum Dots

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ABSTRACT

Generating and detecting a prescribed single-electron state is an important step towards solid-state fermion optics and related quantum information processing. Here, we introduce our recent proposal for an experimentally feasible way of generating a single electron in a Gaussian wave packet, using a quantum-dot pump operating in gigahertz frequency. With the help of a strong magnetic field, the generation is insensitive to the details of nonadiabatic pump operation and the shape of the pump potential. The spatial distribution of the wave packet can be detected by using a dynamical potential barrier.

INTRODUCTION

On-demand single-electron sources have been developed, opening roads toward a fermion version of quantum optics and related quantum processing [1, 2, 3]. Among them, a quantum-dot (QD) pump [4] has the unique property of emitting hot electrons of ~ 100 meV above the Fermi energy. The pump had been originally studied for metrology, and there is growing interest on how to apply it to fermion quantum optics. Its application is plausible as the scattering of hot electrons by phonons and other electrons can be suppressed [5].

For its application, it is crucial to realize a QD pump emitting a prescribed electron wave packet with a useful form. A detector for measuring an emitted packet is also necessary for realizing the fermion optics. In this article, we introduce our recent theoretical proposal [6] for generation and detection of a single-electron Gaussian wave packet using a QD pump.

GENERATION OF A GAUSSIAN WAVE PACKET

A QD pump utilizes a dynamical quantum dot in a twodimensional electron gas (2DEG), which is formed by



Fig. 1: Generation of a coherent state in a typical quantum-dot pump [7]. The dynamical quantum dot is formed by gates **G1** and **G2** (blue, inset) in GaAS 2DEG (green, inset). A strong magnetic field **B**=14T is applied. Gate voltage V_{G1} adiabatically changes in the capturing process of the pump and then abruptly changes in the emission process. The other gate voltage is constant in time. The ground-state electron captured in QD evolves to a coherent state (cone) moving along the $E \times B$ drift (curve) as the barriers rise. This figure is a modified version of a figure in Ref. [6].

gate voltages V_{G1} and V_{G2} ; See Fig. 1. A pump cycle is driven by modulating V_{G1} and consists of two processes; first, electrons are captured in the QD when the entrance barrier is lowered below the Fermi energy, and the captured electrons are emitted through the exit barrier when the entrance barrier is sufficiently raised. The capturing process has been analyzed by the semi-classical rate equation, while the emission process is little studied theoretically.

We analyzed the emission process, by solving the wave packet dynamics of a captured electron in the dynamical QD. Due to the slow capturing process, we could focus on the regime where only one electron is captured adiabatically in the QD. Time evolution of the captured electron in the emission process is not trivial, since the QD confinement potential $U_{\rm QD}$ nonadiabatically changes in time *s*. It is crucial that a strong magnetic field makes the evolution simple and insensitive to process details. At a time s=0 of the capturing process, the electron is in the ground state of the QD, which is the Gaussian state when the cyclotron frequency ω_c is much larger than the QD confinement frequency ω_0 . We find that its time evolution $\psi(\mathbf{r}, s)$ is well described by

$$\psi \simeq \psi_c (\mathbf{r}, s) = \frac{1}{\sqrt{\pi l_B^2}} \exp\left[i\mathbf{r} \cdot \mathbf{p}_c(s) - \frac{[\mathbf{r} - \mathbf{r}_c(s)]^2}{2l_B^2}\right],$$

provided that U_{QD} changes slowly in length scale $l_{\text{B}} \equiv \sqrt{\hbar/(|e|B)}$ (e is the electron charge) and time scale ω_c^{-1} [6]. ψ_c is a coherent state, as $r_c(s)$ and $p_c(s)$ follow the classical $E \times B$ drift motion. When the coherent state gains sufficient energy, it is emitted through the exit barrier and a Gaussian wave packet is generated in the quantum Hall edge (see Fig. 2 (a)) in the regime where the tunneling time through the exit barrier is small. [6].

DETECTION OF A GAUSSIAN WAVE PACKET

An important feature of a Gaussian wave packet is that it satisfies the Heisenberg minimal uncertainty $\hbar/2$. We suggest using the quantum dot pump for experimentally confirming the minimal uncertainty [6].

The energy and time distribution of the emitted wave packet can be experimentally studied by measuring current I_T through a potential barrier induced by gate G3 (see Fig. 2). To obtain the energy distribution, one prepares the potential barrier of time-independent height U_3 and measures $P_E(U_3) \equiv (ef)^{-1} \partial I_T / \partial U_3$. f is the pumping frequency. To obtain the time distribution of arrival at the detector, one rapidly raises U_3 from 0 to a large value (much larger than the energy of the emitted state) at time s_3 and measures $P_T(s_3) \equiv (ef)^{-1} \partial I_T / \partial s_3$. Fig. 2 shows a simulation of the detection. From the energy and time distributions, one can estimate the uncertainty of the measured wave packet, and study whether the un-



Fig. 2: (a) Schematic view of generation and detection of a single-electron Gaussian wave packet. The wave packet is emitted from the pump in Fig. 1. Its energy $(|\psi(\varepsilon)|^2)$ and arrival-time $(A_D(s))$ distributions are experimentally measured by using gate G3 of 200 nm width and voltage V_{G3} . To measure the time distribution, V_{G3} changes 1 V in 50 ps. (b), (c) Numerical results of $P_{\varepsilon}(E)$ and $P_T(s)$, compared with $|\psi(\varepsilon)|^2$ and $A_D(s)$. This figure is a modified version of a figure in Ref. [6].

certainty approaches the limiting value of the minimal uncertainty.

We introduced the general dynamical property of an electron wave packet in a 2D dynamic quantum dot under a strong magnetic field and demonstrated that a Gaussian wave packet can be generated and detected. This generation corresponds to that of a single photon in quantum optics. We believe that this generation will be useful for experimental studies of coherent dynamics of an electron in solid state devices.

References

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