Double quantum dots as a high sensitive submillimeter-wave detector

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A single electron transistor (SET) consisting of parallel double quantum dots fabricated in a GaAs/Al$_x$Ga$_{1-x}$As heterostructure crystal is demonstrated to serve as an extremely high sensitive detector of submillimeter waves (SMMW). One of the double dots is ionized by SMMW via Kohn-mode plasma excitation, which affects the SET conductance through the other quantum dot yielding the photoresponse. Noise equivalent power of the detector for wavelengths about 0.6 mm is estimated to reach the order of $10^{-17}$ W$/\sqrt{Hz}$ at 70 mK.

Single-photon detection (SPD) has been achieved in the far-infrared range by exploiting cyclotron-resonance in a semiconductor quantum dot (QD) in high magnetic fields [3,4]. From the viewpoint of wide application as a detector, it is of great importance to realize SPD without magnetic fields as well as to expand the wavelength range. We demonstrate here that a double QD operated as a single electron transistor (SET) provides a novel mechanism of detecting submillimeter waves (SMMW) with an extremely high sensitivity close to the SPD level in the absence of magnetic fields. The noise equivalent power (NEP) of the detector is estimated to reach the order of $10^{-17}$ W$/\sqrt{Hz}$ for the wavelengths of $\lambda = 0.6$ mm, which well exceeds reported characteristics of conventional detectors in the relevant spectral range.

The mechanism is described by Figs.1 (a)-(c). The device structure shown on Fig.1(a) is reminiscent of a lateral double-QD SET studied earlier at different groups [1,2]. Adjacent to the first QD (D1) that forms SET, the second QD (D2) is placed and capacitively coupled to D1. D2 is coupled to incident SMMW by a planar dipole antenna. As depicted in Fig.1 (b), if an electron in D2 gains an excess energy $E^*$ through the excitation by SMMW, the excited electron escapes either to D1 or to the electron reservoir adjacent to D2 so that the number of electrons, $N_2$, in D2 decreases by one ($\Delta N_2 = -1$). The electron then rapidly releases its excess energy (via phonon emission or electron-electron interaction) relaxing to the Fermi level, $\varepsilon_F$. The potential barriers, in turn, prevent the "cold" electron from returning to D2, thereby realizing a relatively long lifetime $\tau_1$ of the ionized state of D2. Letting $C_{12}$ be an inter-QD capacitance and $C_i$ ($i=1$ and 2) capacitances between D1 and the environments, the ionization of D2 ($\Delta N_2 = -1$) decreases the electrochemical potential of D1, $\mu_1$, by $\Delta \mu_1 \approx -e^2C_{12}/C_1$ ($e$ is the unit charge), where $C_{12} \ll C_1$ and $C_{12} \ll C_2$ hold in the experimental condition. This will result in the shift of SET conductance peak by $-\Delta \mu_1/\varepsilon_{ch} \approx -C_{12}/C_2 = -(3 \sim 15 \%)$ in the sweep of $V_{G1}$, yielding a detectable conductance change as shown in Fig.1(c), where $\varepsilon_{ch} = e^2/C_1$ is the charging energy of D1 that determines the period of the Coulomb conductance oscillations.

The inset of Fig.2 schematically shows the device fabricated through a standard lithographic technique on a GaAs/Al$_x$Ga$_{1-x}$As heterostructure crystal with a mobility of 80 m$^2$/Vs and a sheet carrier density of $n_s = 2.6 \times 10^{15}$ m$^{-2}$ at 4.2K. Light areas indicate metal gates deposited on top of the crystal. Negatively biasing the gates depletes the two-dimensional electron gas (2DEG) below the gates and forms D1, D2, the source (S), the drain (D) and the reservoir (R). The lithographic size of each QD is 0.5 $\times$ 0.5 $\mu$m$^2$, with about 200 electrons in it. The gate B12 defines the inter-QD potential barrier. The control gate, G2, controls not only the electrochemical potential of D2, $\mu_2$, but also defines the potential barrier between D2 and R. Metal leads for G2 and B12 extend over 0.1 mm in length, forming a dipole antenna for D2. The experiments are performed at 70mK by using a $^3$He-$^4$He dilution refrigerator.

FIG. 1. Schematic representations of the SMMW photon detection. (a) An SET consisting of parallel double QDs. (b) Ionization of D2. (c) Conductance peak shift induced by the ionization.

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The dark regions in Fig. 2 display conductance peak traces without SMMW as a function of the bias voltages $V_{G1}$ and $V_{G2}$ for G1 and G2, with a fixed bias voltage for B12 at $V_{B12}$ = -532 mV. As $V_{G1}$ increases, the conductance resonance periodically occurs at the positions where $\mu_1 = \varepsilon_F$, forming a set of dark traces with a spacing proportional to $\varepsilon_{eh} = e^2/C_1$. As $V_{G2}$ increases, each trace shows step-wise small jump in the positive $V_{G1}$-direction at each transition point $V_{G2}^t$ where $N_2$ increases by one ($\mu_2 = \varepsilon_F$). This is because the change $\Delta N_2 = +1$ causes abrupt shift of $\mu_1$ by $+\Delta \mu_1/\varepsilon_{eh} \approx +C12/C2 \approx 10\%$ at $V_{G2}^t$. As a source of SMMW, we use an n-InSb Hall device for most of the studies and a high-mobility GaAs 2DEG Hall bar for spectroscopic measurements, both of which emit relatively narrow cyclotron radiation. The frequency $\omega_c = eB_e/m^* \approx m^*$ (the effective electron mass) is tunable by scanning the magnetic field $B_e$ for the emitters. To guide the SMMW from the emitters to the sample we use an optical scheme similar to that previously described [5]. The SMMW power, $W$, incident on the effective antenna area for D2 (about 0.2 mm diameter) is weak, being roughly estimated to be $W \approx 1$ fW or $3 \times 10^6$ photons per second in a band width of 0.6 ± 0.2 mm when the electrical input power of $P_{in} = 1$ mW is fed to the n-InSb emitter. The SET conductance is measured with an ac-voltage (25 mV and 1 kHz) while SMMW are applied in a square waveform at a lower frequency (7 Hz). We represent the photoresponse by the frequency (7 Hz). We represent the photoresponse by the conductance peak traces $\Sigma$ with SMMW, $\Delta \Sigma \equiv \Sigma - \Sigma_0$, and study it via a double lock-in technique [3]. The wavelength of applied SMMW is in a range 0.6 ± 0.2 mm unless otherwise specified.

Fig. 3 (a) shows a typical photoresponse signal, $\Delta \Sigma$, along with $\Sigma_0$ in a sweep of $V_{G1}$, where $V_{B12} = -532$ mV, $W = 0.3$ fW, and the effective time-constant of the measurements is 1 second. $V_{G2}$ is chosen to be -628 mV, which is close to but higher than a nearest $V_{G2}^t$. In this gate bias condition, the inter-QD coupling $(C_{12}/C_2)$ is smaller than that for Fig.2. It follows that the step amplitude in the conductance peak traces $\Sigma_0$ at each $V_{G2}^t$ ($\Delta N_2 = +1$) is found to be smaller than that seen in Fig.2; viz., $+\Delta \mu_1/\varepsilon_{eh} \approx +C12/C2 \approx 3 \sim 5\%$.

The curve of $\Delta \Sigma$ versus $V_{G1}$ shows that the SMMW causes the conductance peak to shift towards the negative direction of $V_{G1}$ by $3 \sim 5\%$, strongly suggesting the ionization of D2 ($\Delta N_2 = -1$). Though not shown here, we have carefully confirmed that the shape of the $\Delta \Sigma$ versus $V_{G1}$ curve is kept unchanged with increasing $W$ up to 4 fW. The negative peak shift as well as its amplitude, together with the fact that these features are independent of $W$, definitely indicate that $\Delta \Sigma$ arises from the switch between the ground state ($N_2$) and the ionized state ($N_2 - 1$), as we have expected in Fig.1. On the other hand, the amplitude of $\Delta \Sigma$, (studied at the peak position marked by the arrow in Fig.3 (a)) linearly increases with increasing $W$ only in a limited range of weak $W$ but is saturated at higher levels as shown in the inset of Fig.3 (a). The saturation can be reasonably interpreted as a consequence that the rate of photon absorption at D2 exceeds the inverse lifetime, $\tau_1^{-1}$, at $W \geq 1$ fW. The expected curve of saturation, $\Delta \Sigma \propto (1 + (\alpha/W))^{-1}$, well accounts for the

FIG. 2. Conductance peak traces on the plane of $V_{G1}$ and $V_{G2}$. The device studied is shown in the inset.
experimental data as shown by the solid line in the inset of Fig. 3(a), where $\alpha = h\nu/\eta \tau_1$ with the photon energy $h\nu$ and the quantum efficiency of photon absorption $\eta$. Noting $h\nu = 2$ meV and assuming $\eta = 10^{-2} \sim 10^{-3}$ [3], we roughly estimate $\tau_1 = 0.1 \sim 1$ ms.

Additional evidence supporting our interpretation is presented in Fig. 3(b), where $\Sigma$ and $\Sigma_0$ are shown against $V_{G2}$ at fixed $V_{G1}$ (-630mV) and $V_{B12}$ (-530 mV). Here, $\Sigma$ is taken under constant illumination at $W = 2$ fW. The values of $\Sigma_0$ reach the maximum at $V_{G2} = -565.2$ mV, where exact conductance resonance ($\mu_1 = \varepsilon_F$) takes place. In addition, as $V_{G2}$ increases, $\Sigma_0$ shows an abrupt decrease and an abrupt increase, respectively, at the transition points $V_{G2} = -566.5$ mV and $-564.4$ mV, at which $N_2$ increases by one ($\Delta N_2 = +1$ at $\mu_2 = \varepsilon_F$). When SMMW is turned on, the conductance changes significantly on the positive sides of these $V_{G2}$ transition points. The change is exactly the one expected from the removal of one electron from D2 ($\Delta N_2 = -1$), as may be understood from the conductance peak trace schematically illustrated on the upper part of Fig.3 (b).

The $V_{G2}$-range where the photoresponse occurs is limited to a narrow interval on the positive side of $V_{G2}$. This is a general feature found at every transition point, and is interpreted by noting that the ionization energy of D2, $\Delta \varepsilon = \mu_2 - \varepsilon_F$, vanishes at $V_{G2} = V_{G2}^*$ but increases as $V_{G2}$ goes away from $V_{G2}^*$ towards the positive direction. This may lead to a rapid decrease both in $\tau_1$ and in the probability of photo-ionization, restricting the $V_{G2}$-range of the photoresponse as observed.

Excitation spectrum is studied by tuning the wavelength of the cyclotron emission line ($\Delta \nu \approx 1.5$ cm$^{-1}$) from the GaAs/AlGaAs emitter ($m^* = 0.067$ $m_0$) over a range 5 cm$^{-1} < \nu < 100$ cm$^{-1}$. The radiation intensity is chosen to be in a linear response regime ($W \approx 0.2$ fW). Figure 4 shows the $B_\nu$-dependence of $\Delta \Sigma$ at the peak position of the data in Fig. 3 (a), where $B_\nu$ is converted to the frequency, $\nu = eB_\nu/2\pi m^*$. Distinct resonance is found at $n = 17$ cm$^{-1}$ ($h\nu = 2$ meV or $\lambda \approx 0.6$ mm) with a FWHM of $\Delta \nu_{FWHM} \approx 3.5$ cm$^{-1}$. We identify $\nu = 17$ cm$^{-1}$ as the Kohn-mode plasma resonance [4], because the value agrees with the calculation of the bare confinement potential for D2 as well as with the extrapolation of the (plasma-shifted) cyclotron resonance studied in our previous experiments on a similar QD (see Eq. (13) in [3]). We suppose that the initially excited collective motion of electrons is very rapidly transferred to a single electron excitation [5] (within a lifetime of $2\pi \Delta \nu_{FWHM}^{-1} \approx 2.2$ ps), so that the excited electron with $E^* = h\nu = 2$ meV escapes from D2.

The sensitivity of detection is extremely high as suggested from the curve of $\Delta \Sigma$ versus $W$ in the inset of Fig. 3 (a). Furthermore, it is noted to be close to the SPD level by the study of real-time trace of $\Sigma$. As shown in the inset of Fig. 4, photoresponse arises as irregular conductance spikes. Here, the data are taken with a time-constant of 3 ms at $W = 0.15$ fW in the same gate bias condition as that for the marked peak position in Fig. 3 (a). The density of the conductance spikes increases with $W$. The positive spikes are ascribed to the switches, $N_2 \rightarrow N_2 - 1$, although individual events of photon absorption cannot be clearly discerned because $\tau_1 (0.1 \sim 1$ ms) is shorter than the time-constant of measurements. We find that the conductance spikes do not completely vanish in the dark condition, probably, because the sample is not perfectly shielded against the 4.2K-black-body radiation in the present work. Noting the dark switches, we roughly estimate NEP to be of the order of $10^{-17}$ W/$\sqrt{Hz}$.

In conclusion, we have demonstrated ultra-high sensitive detection of SMMW by using an SET consisting of parallel double QDs.

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