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Generation, transmission, and detection of terahertz photons on an electrically driven single chip

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We demonstrate single photon counting of terahertz (THz) waves transmitted from a local THz point source through a coplanar two-wire waveguide on a GaAs/AlGaAs single heterostructure crystal. In the electrically driven all-in-one chip, quantum Hall edge transport is used to achieve a noiseless injection current for a monochromatic point source of THz fields. The local THz fields are coupled to a coplanar two-wire metal waveguide and transmitted over a macroscopic scale greater than the wavelength (38 μm in GaAs). THz waves propagating on the waveguide are counted as individual photons by a quantum-dot single-electron transistor on the same chip. Photon counting on integrated high-frequency circuits will open the possibilities for on-chip quantum optical experiments. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4864168]

Integrated quantum optical circuits are particularly promising for future quantum information technology. The transmission and confinement of microwaves can be achieved by standard lithographic techniques, and strong light-matter coupling has been demonstrated in superconductor and semiconductor circuits. However, single-photon detection that directly measures the quantum properties of light is extremely difficult because of the small photon energy. Therefore, measurements have only been possible by microwave spectral analysis with external equipment. For visible light, integrated circuits with sub-wavelength optical elements are still a challenge, although single-photon counting measurements are more feasible for incident light from free space. Given the trade-off between photon energy and wavelength, the energy and spatial scale in the THz region (wavelengths of 100 μm, photon energies of 10 meV) may be an appropriate frequency range for manipulating both aspects of the wave-particle duality of electromagnetic fields on solid-state devices. Indeed, THz single-photon detection is possible with quantum dot (QD) detectors and extreme THz confinement can be achieved in a microcavity laser based on a planar subwavelength resonant circuit.

A two-dimensional electron system (2DES) in a strong magnetic field is a possible platform for on-chip photon manipulation. This is because a gate-controlled QD in a strong magnetic field serves as a single THz-photon counter. Furthermore, in the energy-dissipationless quantum Hall effect (QHE) regime, the electron system can be a well-localized THz generation source originating from the inter-Landau level (LL) optical transition. Because the electrons are carried by noiseless edge channels without backscattering, the LL emission can become a sub-Poissonian THz generation source. These sub-wavelength THz components can be embedded on a single substrate (GaAs/AlGaAs single heterojunction) with fully suppressed background radiation.

In this work, we demonstrate the generation of THz fields, transmission of THz waves, and counting of THz photons on a single chip (Figs. 1(a) and 1(b)). In the all-in-one chip, THz fields are locally generated by applying a direct current (DC). The fields are coupled to a coplanar two-wire line and transmitted over a macroscopic scale larger than the wavelength. THz waves propagating on the waveguide are counted as individual photons by a QD on the same chip. The DC-driven local THz fields are finally converted to low-frequency single-photon-counting signals.

The device consists of a LL THz diode and a gate-controlled QD that are coupled by a coplanar two-wire waveguide (Fig. 1). The electromagnetic propagation and nanofocusing with the two-wire waveguide has been recently demonstrated in mid-infrared optical devices, where the design has been adapted from microwave technology. The transmission efficiency is mainly determined by two factors: impedance matching to the loads (emitter and detector), and radiation loss. The characteristic impedance $Z_0$ of this waveguide is calculated to be 76 Ω for a wavelength of 38 μm in GaAs. Using the impedance of the QD, $Z_{QD} \sim 30 \Omega$, the transmission coefficient is estimated as $1 - (Z_0 - Z_{QD})^2/(Z_0 + Z_{QD})^2 = 0.81$. Assuming that the impedance of the emission spot in 2DES is comparable to that of the QD, the power transmission efficiency is estimated to be (0.81)$^3$. In addition, the radiation attenuation coefficient for the two-wire waveguide on the GaAs substrate is calculated to be 1.15 dB/L, leading to a radiation loss of 23% for $L = 0.5$ mm. Therefore, including the impedance matching, the total transmission coefficient reaches about 50% for the THz device based on microwave technology.

The QD serves as a single THz photon counter in a strong magnetic field. When a THz photon is absorbed by the QD through plasma-shifted cyclotron resonance, an electron is created in the upper LL and internal polarization takes place. The single-photon absorption events give rise to conductance switches with a typical photoexcited lifetime of 30 μs to 0.1 s at 300 mK. In a magnetic field of 5.2 T, the plasma-shifted cyclotron energy of the QD, $h \omega_{QD} = h \sqrt{(\omega_c/2)^2 + \omega_0^2} + h \omega_c/2$, is estimated to be $h \omega_{QD} = 9.16$ meV, where the plasma frequency observed in a similar QD, $\omega_0 = 1.98$ meV, is used. The resonance linewidth...
of about 5% was observed in the earlier study. The dark switching rate is about 2 counts/s in this study, implying that a THz power of $10^{-20}$ W can be detected in the integrated circuit with a transmission efficiency of 50%. The QD currents are measured by a direct coupled mode during photon counting experiments. Although it is easy to generate THz fields by using black body radiation from a heat source, heat diffusion in solid-state devices makes it difficult to ensure a localized THz source. Therefore, we use LL emission from nonequilibrium edge channels in the dissipationless QHE states.7 The ring-shaped mesa structure of the Corbino geometry restricts the energy-dissipative spot to the confluence of the edge channels.8 The length of the waveguide is 0.5 mm. The waveguide also serves as gate lines for forming the QD (see (d)). To minimize the influence on THz transmission properties, thin gate lines for supplying the DC voltages are orthogonally connected from bonding pads to the waveguide (thickness: 30 nm). (c) False colour electron micrograph of a LL THz diode with a 30-nm-thick top gate (yellow) coupled to the two-wire waveguide (red). The dotted circle shows the confluence of adjacent edge channels (the emission spot). (d) Electron micrograph of the gate controlled QD THz photon counter.

In nonlinear diode behavior caused by the LL splitting, the finite current flowing between the inner and outer contacts indicates the presence of electron transfer between adjacent edge channels in the ungated region. A distinct onset voltage ($V_{\text{onset}} = -6.8$ mV) for the current flowing between two contacts (7 and 10) is observed at an LL filling factor of $\nu = 3$ on the negative side of the source-drain voltage, $V_{\text{7,10}} = -(\mu_7 - \mu_{10})/e$ (Fig. 2(b)), where the filling factor beneath the top gate, $\nu_g$, is set to 2. The critical threshold indicates the strong promotion of the electron transfer between edge channels. From the Landauer-Büttiker formalism in the present geometry, the resistance can be expressed by $R_{\text{7,10}} = h/2(e\nu_g)^2$ at the strong scattering limit. The slope in the current-voltage ($I$–$V$) characteristics at $V_{\text{7,10}} < V_{\text{onset}}$ corresponds to $R_{\text{7,10}} = 1/2 \times 38.7 \, \text{k\Omega}$ for conditions where $(\nu,\nu_g) = (3, 2)$, indicating that the $\nu = 3$ edge channel is fully equilibrated with the $\nu = 2$ edge channels. The deviation of the onset voltage ($V_{\text{onset}} = 6.8$ meV) from the cyclotron energy ($\hbar\nu_0 = 8.7$ meV) will be attributed to the exchange enhanced spin-splitting, $\Delta E_{\text{ex}}$.13

We measured photon-counting rates as a function of the source-drain voltage with the QD photon counter embedded on the same chip (Fig. 2(b)). THz photons are emitted on the...
negative $V_{7,10}$ side with a clear onset, where the electrochemical potential of the outer $\nu = 2$ edge channels is lower than that of the inner $\nu = 3$ edge channels. This can be interpreted with the reconstructed energy structures of the edge channels satisfying the necessary conditions for a vertical LL optical transition as discussed in the Hall-bar geometry (Fig. 3(c)). The spin-flip scattering is promoted but no THz photon is generated. The inter-edge optical transition is expected.

In order to investigate the contribution of thermal radiation, we also measured photon-counting rate as a function of the top-gate voltage (Fig. 3). The applied electric power $P_{\text{applied}}(\nu, \nu_g)$ under the conditions $(\nu, \nu_g)$ is evaluated as $P_{\text{applied}}(3, 1) \sim 4P_{\text{applied}}(3, 2) \sim 1.2 \times 10^{-9}$ W at $V_{7,10} = -8.0$ mV. Assuming that the applied power is mainly converted to thermal energy through acoustical phonon emission, the inter-edge scattering region will be hotter when $(\nu, \nu_g) = (3, 1)$. No definite photon emission was observed for $(\nu, \nu_g) = (3, 1)$, which suggests that thermal radiation is negligible in the present experimental conditions.

We also controlled the THz-field coupling between the emission spot and the two-wire waveguide (Fig. 4). The direction of travel of the edge channels is reversed when the magnetic field polarity is reversed, which shifts the position of the emission spot. We recorded the photon counting signals of the QD for both magnetic-field polarities. When the end of the waveguide is positioned in the near-field region of the emission spot, at a distance of $r < \lambda_d$, the photon counting rate exceeds the dark switching rates. Therefore, the experimental results exclude the contribution of photons straying through the substrate or the vacuum of space, providing evidence that high-frequency THz signals propagating along the coplanar line are counted as individual photons.

In the all-in-one chip, the total energy conversion efficiency from the applied DC electric power to the detected THz power is on the order of $10^{-9}$ around $V_{7,10} = -8.0 < h\omega_{\text{THz}}/e$ mV. The small efficiency is mainly caused by the photon emission probability of the LL diode. Because of the limited detection speed of QD currents in the present setup, the photon counting measurements were restricted near the onset voltage of emission. At $V_{7,10} < h\omega_{\text{THz}}/e = 8.7$ mV, the inter-edge-state scattering will be strongly suppressed by the requirements of the spin-flip process. Controlling the spin states of the edge channels through electron spin resonance or spin-orbit interactions will dramatically affect the photon emission probability.

The photon counting of THz waves confined in metal structures on a solid-state chip surface enables quantum optical experiments on high-frequency circuits. The system can be also combined with an external THz source. Possible experiments include on-chip Hanbury Brown and Twiss
experiments on a Y-junction THz power divider, cavity quantum electrodynamics with a planar THz resonator, or studies of quantum plasmonics in low-dimensional semiconductors or graphenes.

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