Exciton optoelectronic transistor

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We demonstrate experimental proof of principle for an optoelectronic transistor based on the modulation of exciton flux via gate voltage. The exciton optoelectronic transistor (EXOT) implements electronic operation on photons by using excitons as intermediate media; the intensity of light emitted at the optical output is proportional to the intensity of light at the optical input and is controlled electronically by the gate. We demonstrate a contrast ratio of 30 between an on state and an off state of the EXOT and its operation at speeds greater than 1 GHz. Our studies also demonstrate high-speed control of both the flux and the potential energy of excitons on a time scale much shorter than the exciton lifetime. © 2007 Optical Society of America

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As the communications industry continues its shift into optically based systems, the demand for devices that have the capability to process optical signals in an efficient and expedient manner is steadily increasing. The development of optically based devices that can perform all necessary logic operations (i.e., switching, AND/OR operations) in a simple and compact manner are vital to increasing the speed of information processing.

One of the critical devices of electronic logic is the transistor—a three-terminal device with the current through two terminals controlled by the third terminal. There are many proposals for optoelectronic and all-optical transistors, and the modulation of optical signals has been demonstrated by a variety of methods; for reviews see [1,2]. Development of semiconductor-based optical transistors attracts particular interest due to the opportunity to create scalable optoelectronic circuits integrated in a chip. To modulate an optical signal, a monolithic optoelectronic transistor (MOET), which is composed of several devices such as a detector, modulator, resonant tunneling diode, and field effect transistor (FET), has been developed [3]. High-contrast switching on a 1 μs time scale in a MOET with lateral dimensions $\sim 150\ \mu\text{m} \times 300\ \mu\text{m}$ has been demonstrated [3].

In this Letter, we demonstrate experimental proof of principle for an exciton optoelectronic transistor (EXOT). The EXOT exploits a new medium for the transistor operation—excitons—and is based on a new physical principle—control of the exciton flux. It is a scalable, monolithically integrated optoelectronic solution that offers the capability of high-speed processing of optical signals. The first prototype of the EXOT, which is demonstrated here, reaches a contrast ratio of 30 between an on state and an off state with a switching time below 1 ns.

The operation principle of the EXOT is based on controlling the flux of excitons via gate voltage. To achieve functionality in the EXOT, there are two critical device requirements. The first is a sufficiently long exciton lifetime, which allows excitons to travel over large distances exceeding the device dimensions before recombination. The second is the ability to control the transport of excitons. Both these requirements are met in the system of indirect excitons. An indirect exciton is a bound pair of an electron and a hole separated in different quantum wells (QWs) in a coupled QW (CQW) structure or on opposite sides of a single QW. For a review on indirect excitons, see [4]. The separation is achieved by an electric field perpendicular to the QW plane. The electric field is controlled via an applied gate voltage (Fig. 1a).

The spatial separation between the electron and hole layers suppresses the exciton recombination rate by orders of magnitude so that lifetime of the indirect excitons can well exceed 100 ns. The long-lived indirect excitons can travel over tens and hundreds of micrometers as demonstrated in [5–11].

The indirect excitons are dipoles, and therefore an electric field F_z perpendicular to the QW plane results in the exciton energy shift $\delta E = eF_z d$, where d is the exciton dipole moment [12] (for the indirect exci-

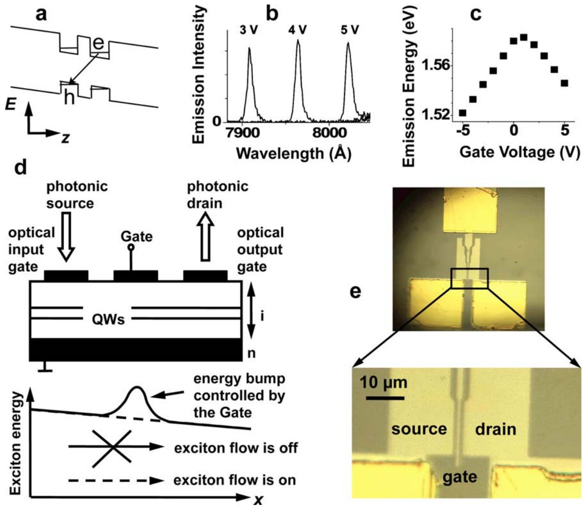

Fig. 1. (Color online) Principle of the EXOT. a, CQW diagram. b, Spectrum of indirect excitons at different applied voltages. c, Energy of indirect excitons as a function of applied voltage. d, Design schematic for the EXOT. e, Top view of the device.

tons in the CQW, d is close to the distance between the QW centers [4]). This allows control of indirect exciton energy by gates: an applied gate voltage controls F_z and in turn the indirect exciton energy (Figs. 1b and 1c). We note that operation principles of general electronic devices are based on electron energy control by gates. A similar control of exciton energy by gates allows the use of indirect excitons in place of electrons in devices. In contrast with electrons, indirect excitons are optically active: they emit photons at recombination and absorb photons at photoexcitation. Since indirect excitons are both optically active and electronically controlled, they can form the basis for building an optoelectronic transistor and, more generally, optoelectronic circuits.

The operation principle of the EXOT is as follows (Fig. 1d). (i) The photons are absorbed at the optical input (source) and create excitons. (ii) Excitons travel from the optical input (source) to the optical output (drain) due to the potential energy gradient $\delta E \sim e(F_{zd}-F_{zs})d \propto (V_d - V_s)d$ created by the difference in the source voltage V_s and drain voltage V_d. The exciton flux from source to drain is controlled by a gate voltage V_g, which controls an energy barrier for the indirect excitons in the region of the gate electrode (Fig. 1d). (iii) Photons are emitted at the optical output by exciton recombination (since the exciton recombination rate is controlled by F_z, see, e.g., [4], optical readout can be driven by applying a voltage pulse to the optical output gate; however this technique is not employed in the demonstration below).

The EXOT has been realized in an $Al_{0.33}Ga_{0.67}As/GaAs$ CQW structure. An n^+-GaAs layer with $n_{Si}=10^{18}\ cm^{-3}$ serves as a homogeneous bottom electrode. The source, gate, and drain electrodes were fabricated on the surface of the structure by depositing a thin semitransparent layer of Pt (8 nm) and Au (2 nm) via e-beam epitaxy. A CQW with 8 nm GaAs QWs separated by a 4 nm $Al_{0.33}Ga_{0.67}As$ barrier was positioned 100 nm above the n^+-GaAs layer within an undoped 1 μm thick $Al_{0.33}Ga_{0.67}As$ layer. (Positioning the CQW closer to the homogeneous electrode suppresses the in-plane electric field near the edges of the electrodes, which otherwise can lead to the exciton dissociation [13].) The source and drain gate were kept at $V_s=2$ V and $V_d=3$ V, and the gate voltage V_g was varied within 0–5 V. The bottom electrode was utilized as a common ground. The transistor gate was 1 μm wide, with 1 μm spacing between both the gate and source and the gate and drain (Fig. 1e).

Laser light excites excitons at the EXOT source. For the excitation, we used a beam of 632 nm He–Ne laser beam focused to a spot $\sim 10\ \mu$m in diameter. The emitted light was diffracted by a single-grating spectrometer and detected by a Peltier-cooled photomultiplier tube and time correlated photon counting system. The exciton's emission energy depends on the gate voltage (Fig. 1b and 1c), which allowed us to distinguish the exciton emission at the drain region, which occurs at 791 nm for $V_d=3$ V. The images of the exciton emission were taken by a CCD with a 790±10 nm filter, which covers the spectral range of the excitons in the source, gate, and drain regions. In time-resolved measurements, the gate voltage was controlled by a pulse generator. The experiments were performed in a He cryostat at $T=1.4$ K. The profiles of the exciton energy were estimated as in [13].

Results of the experiment are shown in Figs. 2 and 3. Figures 2(a) and 2(b) present the control of the flux of indirect excitons across the gate. A contrast between the output signal in an on state at $V_g=5$ V and off state at $V_g=0$ is shown in Fig. 2(c). In the experiment with pulsed gate voltage, an exponential time constant on the rising edge was $\tau_e \sim 160$ ps and a 10/90 rise time was $\tau_{10/90} \sim 400$ ps (Fig. 2d), which indicates that this device is functional at GHz frequencies. The transfer characteristics of the EXOT for V_g ranging from 0 to 5 V demonstrates an on/off contrast ratio of up to 30 (Fig. 3a). The results agree with our modeling of the electric field profile (Fig. 3b): our estimation suggests that the bump in poten-

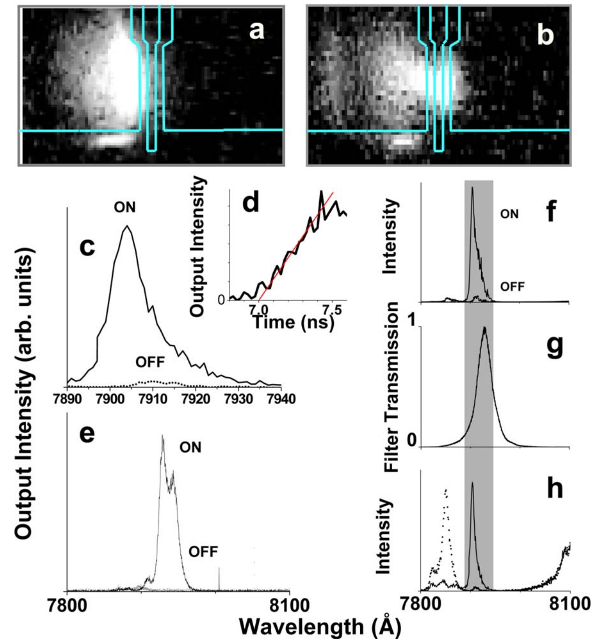

Fig. 2. (Color online) Experimental proof of principle of the EXOT. a, Emission image at the EXOT in the off state, $V_g=0$. b, Emission image at the EXOT in the on state, $V_g=5$ V. Excitons travel from the source to the drain when the EXOT is in the on state. Images were taken by CCD, using an interference filter with transmission band 790±10 nm. c, Output spectra for the EXOT in the off state, $V_g=0$ (dotted), and on state, $V_g=5$ V (solid), demonstrating on/off contrast. The emitted light was collected at the drain region by using the spectrometer slit for the spatial filtering. e, Similar data for device 2 with interference filtering. The interference filter was built to fit to the spectral area of the EXOT output shown by the gray box in f–h. f, Filtered broad range spectra of the off/on states. g, Interference filter transmission. h, Broad range spectra of the off/on states without the interference filter. d, Time-resolved output intensity (measured at 791 nm), demonstrating the switching speed of the EXOT. The thin line is a guide for the eye. All data except those in panel e refer to device 1. Input laser power $P_{input}=430\ \mu$W, $T=1.4$ K, $V_s=2$ V, and $V_d=3$ V for the data.

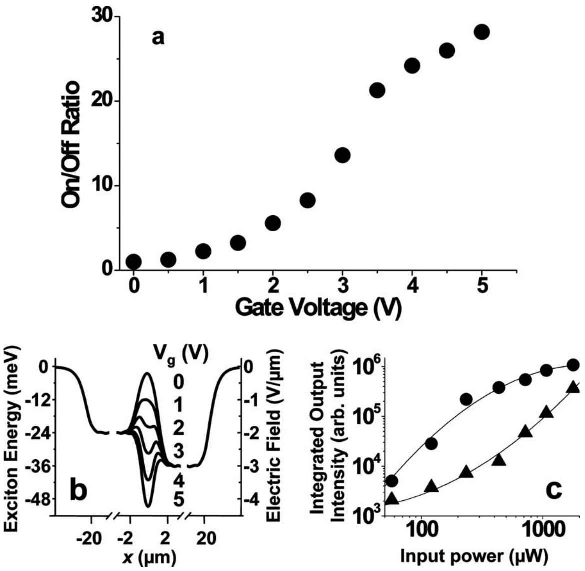

Fig. 3. Characterization of the EXOT. a, Integrated output intensity of the EXOT as a function of gate voltage V_g normalized to that of the EXOT in the off state at $V_g=0$. Input photon power $P_{input}=435$ μW. b, Modeled profile of potential energy of the indirect excitons (left axis) and electric field F_z (right axis) for $V_g=0-5$ V. c, Integrated output intensity for the EXOT in the off state (triangles), $V_g=0$, and on state (circles), $V_g=5$ V, as a function of P_{input}. Thin curves are a guide for the eye. $T=1.4$ K, $V_s=2$ V, $V_d=3$ V, and spectral integration range is 789–794 nm for the data.

tial energy between the source and the drain disappears around $V_g=3-4$ V, which corresponds to the region of greatest increase in output photon intensity. Our results also demonstrate that the EXOT is operational over a wide range of input powers (Fig. 3c) (Following [14], "operational" is defined as capable of contrast greater than 3 between on and off states.)

While the Letter reports the proof of principle for an optoelectronic transistor based on the modulation of exciton flux via gate voltage and for high-speed control of both the flux and potential energy of excitons on a time scale much shorter than the exciton lifetime, in this paragraph we briefly address possible limitations. Obviously, the control of excitons can be done only in the temperature range where excitons exist, i.e., at temperatures roughly below E_X/k_B, where E_X is the exciton binding energy and k_B is the Boltzmann constant [15]. For instance, for the indirect excitons in the $Al_{0.33}Ga_{0.67}As/GaAs$ CQW structure E_X/k_B is of the order of 40 K [16]. Note that E_X can be varied in different structures by choosing different semiconductor materials and different structure parameters [4]. Note also that low-quality samples may exhibit poor quantum efficiency at elevated temperatures [4] and therefore high-quality samples with a low nonradiative recombination rate are required for optimal device operation at high temperatures.

In conclusion, we have demonstrated experimental proof of principle for an optoelectronic transistor based on the modulation of exciton flux by gate voltage. The exciton optoelectronic transistor (EXOT) implements electronic operation on photons by using excitons as intermediate media: the intensity of light emitted at optical output is proportional to the intensity of light at optical input and is controlled electronically by the gate. We have demonstrated a contrast ratio of 30 between an on state and an off state of the EXOT and its operation at speeds greater than 1 GHz. Considering that the geometry of the device mirrors that of a FET, the EXOT has the potential to be integrated into circuits in a similar manner, thus providing an opportunity to create high-speed optoelectronic integrated circuits for optical signal processing. Optimization of the device parameters and the development of switching, amplification, and logic operations including those at high temperatures is a subject for future work. A fundamental result of the experiment is a demonstration of control of exciton fluxes and potential energy reliefs for excitons on a time scale much shorter than the exciton lifetime. This opens pathways for studies of excitons in *in situ* controlled traps, trap lattices, and other potentials.

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