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Optically induced charge transport through submicron channels

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Abstract

We report on optically induced charge transport measurements through conducting submicron channels in AlGaAs/GaAs heterostructures. The channels are defined within a two-dimensional electron gas in a quantum well by chemical etching. By applying a voltage to a top gate, the channels can be depleted electrostatically. We present two different heterostructure designs and two processing techniques to build nanostructured optoelectronic detectors. We demonstrate the suitability of our devices for optically induced charge transport measurements in the mesoscopic regime.

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Since 1988 it is well known that n-type channels with a width of only a few times the electron Fermi wavelength show a quantization of the conductance at low temperature [1,2]. Shortly afterwards it has been demonstrated that far-infrared radiation can induce a current across such quantum point contacts [3]. Then, the quantum point contacts were defined in a two-dimensional electron gas (2DEG) by a split gate technique [4]. Here, we demonstrate how to nanostructure an n-doped quantum well to form narrow one-dimensional channels by etching techniques. We show that in such channels a laser field with photon energy close to the interband energy of the quantum well induces a current across the channels.

As depicted in Fig. 1, the channels are defined by a lateral constriction within a 2DEG within a quantum well. The two-terminal differential conductance across such a channel is determined by a standard lock-in technique. Applying a voltage to a top gate, the chemical potential of the electron states in the channels is shifted with respect to the Fermi energies of the source/drain contacts. The thickness of the top gate is chosen such that the gate is opaque for the laser light. In one of the two leads of the channel, an aperture with a diameter of about 2 μm defines the position, where electron–hole pairs are optically excited in the quantum well. The aperture is wider than the optical wavelength to avoid plasmonic effects in the metal top gate [5].

Starting point is AlGaAs/GaAs heterostructures which contain a 2DEG each. The 2DEGs are located 40 nm (devices I, III) or 95 nm (device II) below the surface of the heterostructures (Figs. 2(f) and (g)).

The channels in the devices I and II are defined by a combination of e-beam lithography and chemical wet etching. Herein, the top layer of the heterostructures is locally removed at a depth of 20–60 nm, a step which locally passivates the top doping layer and destroys the 2DEG underneath. The lithographic width of the remaining conducting channels is approximately 350 nm (Figs. 2(a) and (b)). In a consecutive lithographical step, a gold top gate with a thickness of 110 nm is evaporated across the channel and the leads.

Device III is defined by a dry etching technique. First, a 30 nm thick gold top gate is defined by e-beam lithography (bright rectangles in Fig. 2(d)) with a nickel layer on top to protect the underlying 2DEG. An anisotropic reactive ion

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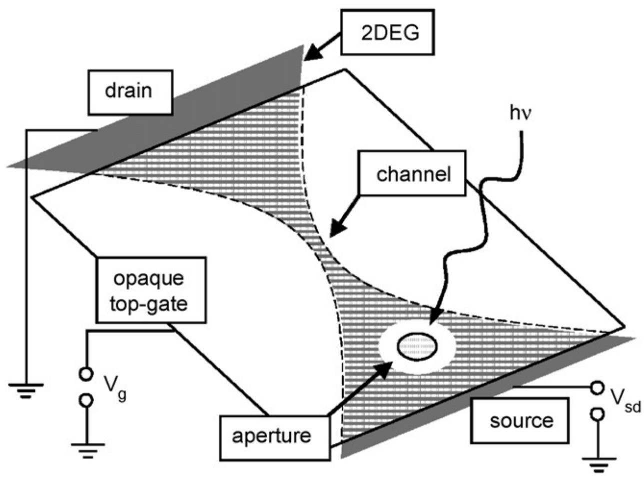

Fig. 1. Experimental circuit. A lateral constriction in a 2DEG between source and drain contacts forms a low-dimensional electron channel. The central area of the device is covered with an opaque top gate (bright rectangle). An aperture in the top gate close to the constriction defines the position where the underlying 2DEG is optically excited.

etching using $SiCl_4$ creates a lateral channel by removing the unprotected top layers of the heterostructure. Then, an isotropic wet etching step with 1% hydrofluoric acid selectively removes the sacrificial layer of the heterostructure (Fig. 2(f)). The resulting underetch of approximately 2 μm appears as pale regions of the leads in Fig. 2(d). The remaining free-standing channel has dimensions of 4 μm × 600 nm × 130 nm (length × width × height, Fig. 2(e)).

Fig. 3(a) shows the differential conductance of device I as a function of the voltage V_g applied to the top gate, after the device has been illuminated with a 633 nm He–Ne laser. We find that the conductance versus V_g graph exhibits a kink at $V_g \sim -1$ V (black arrow).

We interpret the finding in a way that although the top gate depletes the channel at $V_g \sim -1$ V, there still remains a remenescent conductance for $V_g < -1.1$ V. We attribute this behaviour to the existence of the second δ-doped donor layer below the 2DEG (see Fig. 2(f)). This layer is not affected by the shallow wet-etching and it gives rise to a parallel conductance after illumination. Such a parallel conductance prevents a meaningful optoelectronic measurement across submicron channels.

There are two strategies to overcome the parallel conductance problem: one solution is to underetch the channel in order to passivate the second δ-doped donor layer (device III), and the second solution is to utilize a heterostructure with only a top δ-doped donor layer (device II).

Fig. 3(b) shows the differential conductance of the underetched device III in the case with (G_{on}) and without (G_{off}) optical excitation. For the photon excitation a titanium:sapphire laser is used at a wavelength of $\lambda = 780$ nm, a repetition rate of 75 MHz and an optical power of about 1 nW (~ 300 W/m^2) shining on the device. Evidently, there is an additional laser-induced contribution to the conductance, which still can be pinched off at

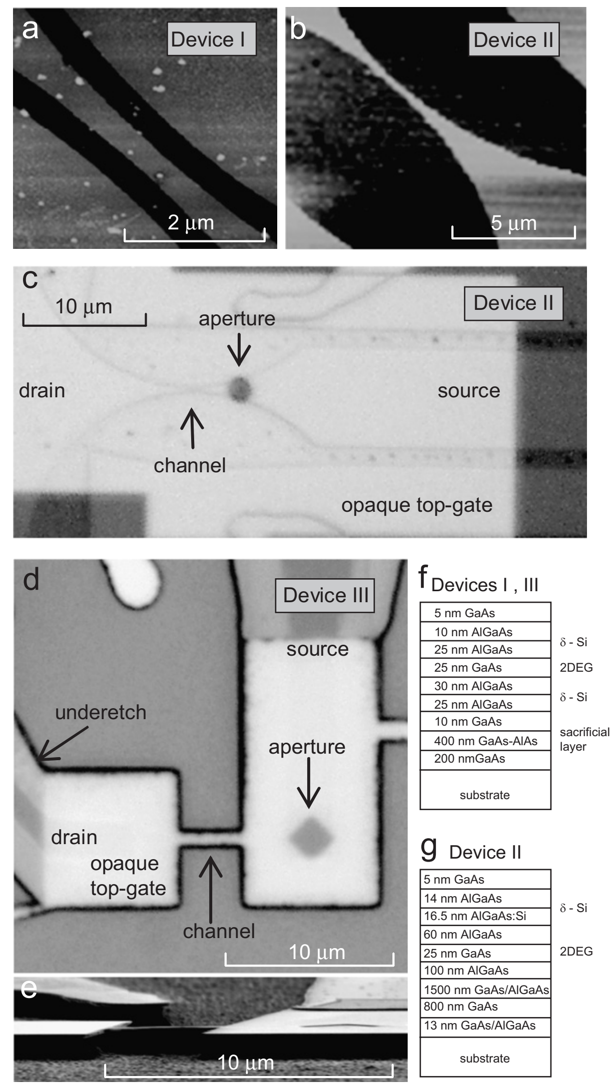

Fig. 2. Device geometries for optoelectronic transport experiments. (a) and (b) AFM-micrographs of wet-etched trenches, which define the channel: (a) device I contains a 350 nm wide channel and (b) device II a 325 nm wide channel. (c) SEM top view of device II showing the gold gate (bright) covering the heterostructure (dark). (d) SEM top view of device III. The opaque top gate covers the central region of the device. Underetched regions appear as pale areas. (e) SEM micrograph of a comparable device taken under a tilt angle of 87°. (f) and (g) Schematic of the employed heterostructures.

$V_g < -1.2$ V. Therefore it is generally possible to use two-side doped, but underetched heterostructures (Fig. 2(f)) for photoinduced transport experiments.

The shallow-etched device II also can be pinched off at a similar laser excitation (Fig. 3(c)). We attribute the finding to the improved heterostructure with no second donor layer below the 2DEG. Additional step-like structures in G_{off} of device II are caused by the formation of one-dimensional sublevels in the channel [1,2]. After subtracting a serial resistance of about 1.5 kΩ these steps take values at multiples of the universal conductance quantum $G = 2e^2/h$ [1,2]. The one-dimensional features are clearly smeared out under photon illumination. The photo-induced

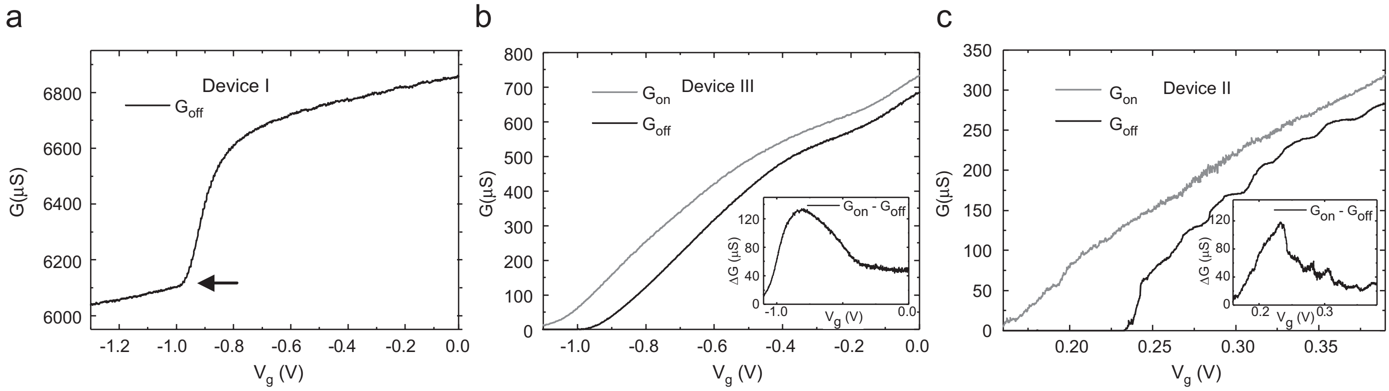

Fig. 3. Differential conductance across the devices I–III as a function of the top gate voltage V_g at $T = 3.8\,K$. (a) Device I: after illumination, the channel cannot be pinched off. (b) Typical depletion curves of the underetched device III. Laser illumination increases the conductance at a given V_g. Nevertheless, the channel can still be pinched off at $V_g < -1.2\,V$. The inset shows the difference between the conductance during and without laser illumination. The difference is maximum close to pinch off. (c) Device II's behaviour resembles qualitatively the one of Device III but shows additionally distinct features, even in the case of illumination (G_{on}). Considering a serial resistance of approximately $1.5\,k\Omega$ reproduces the well-known one-dimensional subband plateaus of multiples of $2e^2/h$. The inset shows the difference between the conductance with and without laser illumination.

conductance is obtained by subtracting G_{off} from G_{on}, as is shown in the insets of Figs. 3(b) and (c). For both devices III and II, the photoinduced conductance reaches its global maximum close to pinch-off and declines to zero when the channel is pinched off. Future experiments aim towards understanding the features in Fig. 3 as a function of temperature, source/drain bias and laser excitation.

In conclusion, we have tested different processing techniques of submicron channels defined in a semiconductor heterostructure. We find that both underetched and specifically designed heterostructures are suitable for optically induced transport experiments across low-dimensional channels since both techniques allow suppressing parallel conductance.

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