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Review

Fabrication of CdMgTe/Cd(Mn)Te nanostructures with the application of high-resolution electron-beam lithography

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ABSTRACT

In this work we report on fabrication of quantum wires and quantum point contacts from the modulation doped CdMgTe/Cd(Mn)Te structures, with the application of a high-resolution *electron-beam lithography*. We emphasize on methods which were not yet utilized for these substrate materials. In particular, we describe the so-called shallow-etching approach, which allows for the fabrication of quantum constrictions of a physical width down to 100 nm, which are characterized by the smoother confining potential as compared to the deep-etched devices. For that purpose, a single-line exposure mode of electron-beam lithography has been used. We demonstrate also, how to combine the etching of separating grooves with the thermal evaporation of metal side-gates into a single post-processing stage of a quantum point contact fabrication.

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Contents

1. Introduction

Modulation doped CdMgTe/Cd(Mn)Te quantum wells (QW) combine the high mobility of two dimensional electron gas (2DEG) with an extremely large and tunable Landé g-factor [1]. Such unique properties make this type of heterostructure a very promising candidate for experimental studies of a spin-dependent quantum transport in lithographically patterned sub-micron devices, as well as optoelectronic devices for an infrared range and terahertz spectroscopy [2–4]. However, for MBE grown CdMgTe/Cd(Mn)Te materials, a special pre-and post-processing procedures are required at all technological stages of nano-patterning. One of the reasons is that II–VI semiconducting alloys are characterized by the high inter-diffusion coefficients and the low defect formation energies [5]. Therefore, in contrast to III-V compounds, relatively low temperatures are required at all technological stages during the nano-structurization phase [6]. This makes the assembly of quantum devices more difficult and there are relatively few experimental studies, devoted to the properties of one- and zero-dimensional nanostructures fabricated of the above mentioned materials [7].

Furthermore, the limitations of processing temperature pose a serious problem with the application of high-resolution of electron beam lithography (EBL). Typical spintronic device, formed from QW, consists of multi-terminal quasi-ballistic junction covered with metallic top gate, which is used for the modulation of a

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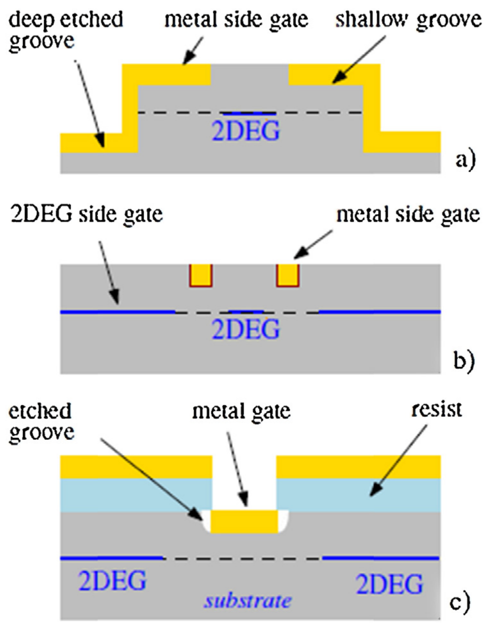

Fig. 1. Schemes of applied lithographical methods. (a) Combination of a deep- and shallow-wet etching used for mesa definition and side gate fabrication. One-dimensional conducting channel (1DEG) is in the central part, dashed line indicates the position of a quantum well. (b) Combination of metal and 2DEG side gates, very narrow separating grooves (filled with metal) are defined using the *single-pixel* line mode of EBL. (c) Wet etching and lift-off metallization combined into a single lithography step. Note that for all processing stages the active region of the device (2DEG) is never exposed to the high-energy electron beam.

2DEG density [8]. Therefore, when gate area is defined lithographically, the active area of a device is exposed to the high-energy electron beam. Clearly, such procedure may be not compatible with e-beam lithography of a CdMgTe/Cd(Mn)Te structure since the large part of electron energy is dissipated in the junction area, generating heat.

In this work we propose to overcome the above mentioned incompatibilities by the following approaches:

- Elimination of the top-gate geometry from the device design. The 2DEG density is controlled by the application of *side-gates*, either metallic or formed from adjoint 2DEG areas which are isolated electrically from the conducting channels by a separating groove. For such arrangement, the active area of a device is never exposed to the high-energy electron beam.
- Reduce the number of processing steps by combining the side gate evaporation and lift-off procedure with the shallow wet-etching stage.

The proposed approaches are summarized in Fig. 1.

2. Materials and methods

Investigated structures were patterned from the 30-nm-wide Cd(Mn)Te quantum well, with a manganese content of $x = 0.3\%$, which resided 138 nm below the sample surface. The structure was grown by a molecular beam epitaxy (MBE) on a commercial expired (100) – GaAs substrate and the quantum well was modulation doped on one side with iodine and embedded between Cd(Mg)Te barriers. On such structure four-terminal quantum wires and point contacts of the variable length L and the lithographic width W have been patterned by e-beam lithography using shallow- and deep-etching techniques followed by a metal evaporation combined with so-called *lift-off* process.

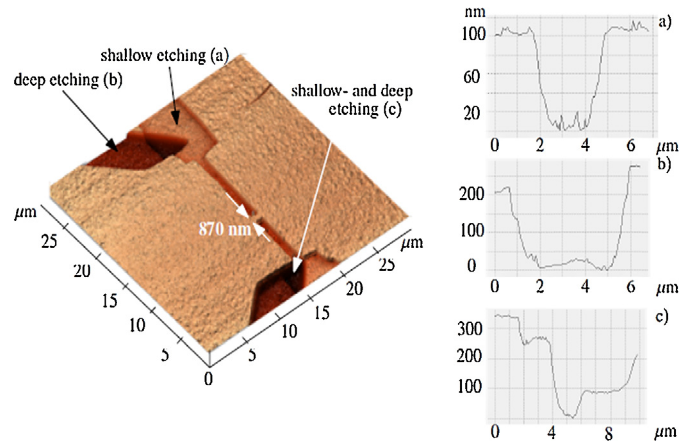

Fig. 2. Atomic force microscope image of a quantum wire fabricated on a CdMgTe/Cd(Mn)Te substrate by combination of shallow and deep with wet etching and PMMA as an etching mask (left). For deep etching 5% PMMA solution was used. The depth profiles along the separating grooves (right).

As a high-resolution positive tone resist we used a polymethyl methacrylate (PMMA) organic polymer, commonly used in electron-beam lithography [9]. Usually, PMMA is dissolved in chlorobenzene or anisole to create a casting solution which is deposited onto substrates with spin-on process. After spinning, resist undergoes a pre-bake process, typically of about one hour at 180 °C. However, keeping in mind the above mentioned limitations of processing temperature, we *reduced the pre-backing time* to about 5 min. As a resist film, 3% and 5% 950k PMMA solutions in anisole, spinned-on at 6000 rpm, have been used.

The patterns have been exposed with the acceleration voltage of 30 keV using the size dependent dose and a beam current. In order to obtain the narrowest possible separating grooves we applied a so-called *single-pixel line* mode of EBL, an example of quantum point contact (QPC) defined this way is shown in Fig. 2. The exposed line dose in the constriction area has been reduced in order to correct for a so-called *proximity effect*, which is especially important for materials with the high average atomic number Z ($Z = 50$ for CdTe).

Patterns have been developed by 60 s in a standard MIBK/isopropanol solution (1:3) at 21 °C. For the subsequent wet etching 0.05% Br_2 in glycol ethylene has been applied. A large area separating grooves and alignment marks have been deep-etched, i.e., the depth of trenches was larger than quantum well deepness, whereas the active regions of the devices have been shallow-etched, above the well. Wet etching with bromine alcoholic solutions is known to be approximately isotropic and does not induce undesirable changes in properties of the material [10]. Therefore, it is preferred over dry-etching and produces desirable undercuts, which in turn can be used for a side-gate metal deposition, see Fig. 1c. As a gate material we have used a Ti/Au bilayer deposited with the application of argon ion sputtering method and finally, gates are formed after the lift-off of resist mask performed in warm acetone.

3. Results and discussion

One-dimensional semiconductor quantum channels are usually defined with the application of split-gates or by etched mesa structures which are additionally covered with metal gates. The later method is preferred for the devices with a complicated geometry like multi-terminal quasi-ballistic junctions or spintronic structures [8,11]. In this case the usage of shallow etching is favorable since for the deep mesas a strong surface depletion occurs and a reduction of mobility by the sidewall scattering is observed [12].

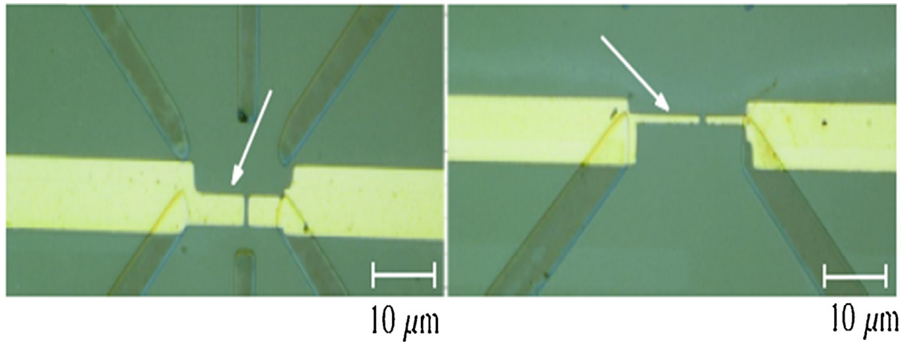

Fig. 3. Optical microscope images of Ti/Au (10/40 Å) metal gates fabricated with the application of a lift-off technique. Arrows indicate side-gates of length of 4 µm and 1 µm which are evaporated directly to the shallow the etched grooves (compare Fig. 2).

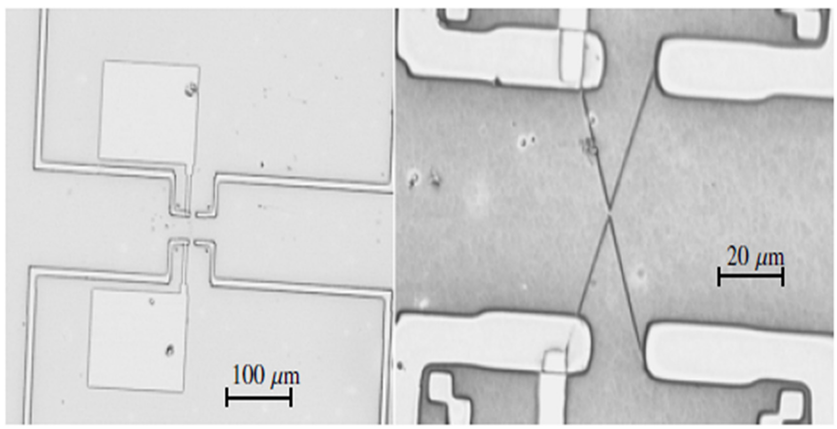

Fig. 4. Optical microscope images of quantum point contact (QPC) fabricated with the single-line EBL exposure of 3008 pC/cm dose on 3% PMMA. As in Fig. 3 deep and shallow etched grooves are filled with Ti/Au (10/40 Å) film. Left part shows contact pads for metal side gates, which are within larger areas assigned for contacting the 2DEG side gates. Enlarged image of V-shaped QPC is shown on the right.

Fig. 2 shows the combination of a shallow- and deep etching performed on the same wafer in separate lithography steps. Deep mesas (200 nm depth) were prepared within the large (1 mm × 1 mm) writing field (WF) where separating grooves of contact pads and alignment marks were exposed on a thick resist (0.56 µm). Shallow mesas (100 nm depth) were defined within small WF (64 µm × 64 µm) on a thin (0.15 µm) PMMA layer. The width W of a fabricated quantum wire was reduced from 1000 nm after the development to final 870 nm after processing, indicating that the lateral etching distance was of about 60 nm. From that, we have estimated the degree of anisotropy as $A = 0.6$ together with the etch rate of about 0.02 nm/min.

From the depth profiles of our nanostructures shown in Fig. 2 we conclude that the etch rate was independent on the trench width and that the etch depths in the central part of the separating groove and close to the mesa edge are similar. Note also, that the surfaces of nanostructure outside the shallow and deep trenches are rather flat, indicating a good adhesion of a resist mask to the substrate material, in spite of the reduced time of PMMA pre-backing. Otherwise, an etchant may find its way under the mask and round the mesa edges out.

In the next step of processing we have filled the etched grooves with electrostatic side-gates using metal deposition and *lift-off* technique. In this case, the required undercut below the resist mask has been naturally formed by lateral etching, as explained in Fig. 1c. The results are summarized in Fig. 3 and as it is seen, the lift-off procedure was successful on the whole device. We have checked that the metal bilayer is continuous also in the regions where shallow- and deep-etching overlaps and the gate surface goes far below the sample surface. We have used this method to fabricate the one-dimensional electron channels (quantum wires) of length $L \geq 1$ µm.

To assemble devices of a sub-micron length we have applied *a single-pixel line* mode of EBL in order to obtain the narrowest possible separating grooves and sharp gate tip at the constriction site. Results of such approach are shown in Fig. 4. For this particular design, the width of the point contact can be controlled by metal side gates which fill up single-line grooves and by side gates "made off" 2DEG electrons, which reside in a quantum well, on the other side of a very narrow separating trench. Here we applied a very shallow etching depth (30 nm) and the narrowest obtained line has the width of 86 nm as obtained from the SEM imaging. Since the estimated degree of anisotropy is approximately 0.6 we conclude, that the resolution limit of our lithographic procedure is about 50 nm (on 0.15 µm thick 950 k PMMA). Finally, it must be stressed, that energizing simultaneously both types of gates, allows for controlling the shape and strength of the confining potential, which is an important advantage of the proposed design.

4. Summary and conclusions

To conclude, we propose the electron beam lithography (EBL) recipes which are specially designed for the post-growth processing and nano-patterning of Cd(Mn)Te quantum wells in order to overcome the limitations of processing temperature of II–VI semiconductors. The novel lithographic methods proposed here are based on the combination of deep and shallow wet etching and the side gate evaporation with the lift-off technique to obtain trenches and gates in the reduced number of lithography steps.

We also show that the single line EBL exposure mode can be successfully applied to produce a very narrow and sharp separating grooves. Such trenches, filled with metal gates, can be used to control the electron density and the shape of confining potential. With this approach we have obtained the high resolution lines of 50 nm width and 3:1 aspect ration in developed PMMA resist, with reduced post-backing time. We have demonstrated also that the wet etching depth is spatially uniform for the wider lines and larger rectangles (W,L) $\geq$ 1 μm. This shows that the proposed recipes can be used for the fabrication of the so-called hybrid structures for which the quasi-ballistic quantum channels are integrated with the metallic micro-magnets into a single spintronic device. Moreover, the CdMnTe QW nanostructures are a promising candidate for the construction of the nano-device, e.g. for nano-electronics and opto-nano-electronics.

Acknowledgements

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