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Fabrication and Irradiation Effects of Field-Induced Two-Dimensional Electron Gas in Dopant-Etched Modulation-Doped GaAs/AlGaAs Heterostructures

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Abstract

Suppression of the persistent photoconductivity in GaAs-based two-dimensional electron systems is indispensable for performing advanced quantum manipulation of electron spins states transferred from photons and achieving a photon-spin quantum interface. We propose and fabricate an improved field-induced two-dimensional electron gas in dopant-etched modulation-doped GaAs /AlGaAs heterostructures with simplified ohmic contacts fabrications. We successfully induce a two-dimensional electron gas while it decays with time due to the interface states. Moreover, we evaluate the effects of the light irradiation on the transport properties towards quantum state transfer utilizing GaAs lateral quantum dots.

1. Introduction

Lateral quantum dots (QDs) formed in semiconductor heterostructures, which have great advantages in electrical controllability, scalability, and compatibility with nanophotonic structures, are attractive for developing the quantum interfaces between single photons and electron spins. Recent progress in GaAs QDs have demonstrated the transfer of angular momentum from single photons to single electrons [1,2], and coincident detections of the single photons and single photoelectrons in a QD generated from polarization-entangled photon pairs [3].

One of the current difficulties in photon-spin transfer to the GaAs-based QDs is persistent photoconductivity (PPC) resulting from exciting impurity states formed by Si dopants - Al complexes in AlGaAs layers, namely DX centers [4]. PPC causes the persistent increase of the two-dimensional electron gas (2DEG) density surrounding the QDs, and finally screen fine-gate voltages confining electrons in the QDs by forming the parallel conducting channel in the AlGaAs layer. As a result, readjustment of gate voltages for the QDs is necessary after a certain number of photons irradiation [5]. In the worst case, warming and recooling of devices is needed to erase the PPC. This problem must be solved to acquire a number of photoelectron detection data sufficient to prove the coherent quantum state transfer from single photons to electron spins.

Since these problems are caused by Si dopants, utilizing QDs formed in undoped structures are the most promising solution. On the other hand, fabricating ohmic contacts to the field-induced 2DEG in conventional undoped structures needs the optimizations of etched side-wall profile, ashing, and angle evaporation processes [6]. This fabrication difficulty increases the possibility of current leakage between the ohmic contacts and the top gates, and electrical disconnection between the 2DEG and ohmic contacts.

Here, we propose and fabricate the improved field-induced 2DEG in dopant-etched modulation-doped GaAs/AlGaAs hetero-structures taking advantage of a conventional doped structure to simplify ohmic contact fabrications. Similar 2DEG system has been already reported utilizing an AlAs etch-stop layer [7]. However, we have succeeded in forming a field-induced 2DEG using the standard modulation-doped heterostructure without any special etch-stop layers. This presents the possibility of easy, rapid and wide utilization of undoped 2DEGs. Moreover, we examine the irradiation effects of the proposed field-induced 2DEG system as a first attempt for overcoming the above-mentioned problems on photons irradiation for quantum state transfer.

2. Device structures and fabrications

We use a conventional modulation-doped single heterostructure. The depth of the 2DEG from the surface is 90 nm and the thickness of AlGaAs spacer layer is 35 nm. The devices have been fabricated by etching away the modulation-doped n-AlGaAs layers except for the ohmic contact region, followed by evaporating thin gate electrodes on the etched undoped AlGaAs spacer layers after depositing an insulator layer. The insulator is a 65-nm-thick Si_3N_4 layer formed by a catalytic chemical vapor deposition method immediately after a buffered HF (BHF) treatment on the etched surface. A schematic cross-sectional view of this structure is shown in Fig. 1. The field-induced 2DEG is formed in the etched GaAs/AlGaAs heterointerface, where Si dopants do not exist above, by applying a positive voltage to the gate electrode. Simple and stable ohmic contacts to dopant-induced 2DEG in the unetched doped region are formed by the conventional annealing metallization procedure of AuGe/Ni. The 2DEG channel is formed by smoothly contacting the dopant-induced 2DEG to the field-induced 2DEG.

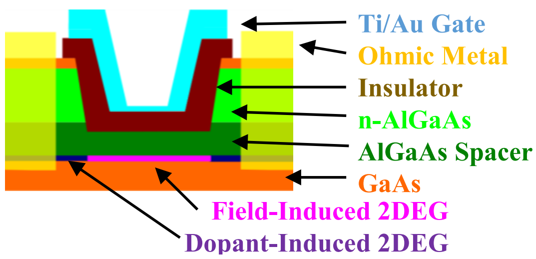

Fig. 1 A schematic cross-sectional view of the device structure.

Since this structure does not contain any etch-stop layer above the AlGaAs spacer layer, one of the important processes is the precise wet etching which provides a few nm etching depth control and smooth etched surface to successfully induce a stable 2DEG under the etched surface. We achieve such etching process utilizing ozone ashing, the BHF treatment before etching, and the citric acid etching solutions. A root mean square roughness of the etched surface produced by this etching method was about a few Å. The reduction of the density of semiconductor/insulator interface states is also crucial for the formation of a sufficiently stable 2DEG with high mobility.

3. Experimental results and discussion

First we observed the field-induced current between the source and drain by a applying positive voltage on the top-gate electrodes at low temperatures. However, it was found that the source-drain current double-exponentially decayed with time constants of 2300 s and 320 s and finally became zero. The behavior of the current decay was changed by different etched surface treatment conditions. Subsequently, we successfully proved the formation of the 2DEG in the fabricated device by observing quantum Hall effects and characterized the 2DEG from the magnetotransport properties shown in Fig. 2. The electron density of 6.8×10^{10} cm^{-2} and the electron mobility of 4×10^{4} cm^{-2}/Vs were evaluated at the gate voltage $V_g = 5$ V. These values were approximately 35 % and 4 % of the electron density and the mobility of the original dopant-induced 2DEG, respectively. With a careful analysis of the magnetotransport data, the decay of the electron density with time constants similar to those observed in the source-drain current decay was seen, indicating that the decays in the current and the electron density occurred in the 2DEG channel. We infer that this current decay and decrease of electron density result from the screening of gate voltage by electrons trapped at the interface states. The obtained low mobility might be attributed mainly to two reasons: the very shallow 2DEG due to a thin AlGaAs spacer layers of only 35 nm thickness and the Coulomb scattering from electrons trapped at the semiconductor/insulator interface states. Therefore, utilizing the substrate with a wider spacer layer is a route to achieve the 2DEG with high quality.

In the end we evaluate the influence of light irradiation on the magnetotransport properties of the induced 2DEG at various gate-voltage conditions. Irradiation was performed at a low temperature by a light emitting diode (LED) whose wavelength was approximately 800 nm. From the analysis of the results for irradiation at zero gate voltage we observed that PPC was successfully suppressed as expected. The rate of persistent increase in the carrier density was reduced to 1/5 of the result in the original doped 2DEG. Furthermore, since the deviation from the quantized Hall resistance at filling factor $\nu = 2$ was only 1.2 % or less, we infer that parallel conduction channels were not formed by the irradiation [4]. From these results, the problem in regards to DX centers seems to be almost solved by this proposed structure. However, in the case of irradiation when 2DEG is induced, the source-drain current rapidly decayed to zero immediately after irradiation. We have considered that this behavior results from the trapping of electrons exited from 2DEG by irradiation and drifting to the interface, and it would be improved by the surface passivation process.

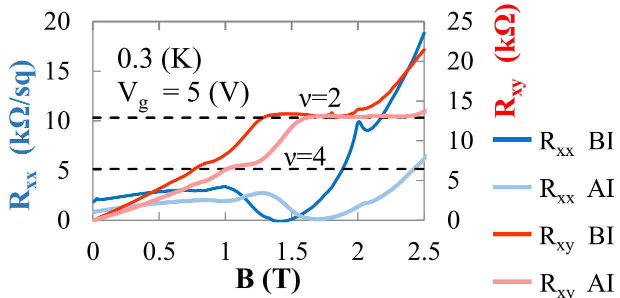

Fig. 2 Hall resistance R_{xy} and longitudinal resistance R_{xx} before irradiation (BI) and after 180 s irradiation (AI) at zero gate voltage. Dashed lines show the thoritical value of quantized R_{xy} at each filling factor ν.

3. Conclusions

We proposed and formed a field-induced 2DEG under a dopant-etched conventional GaAs/AlGaAs heterostructures such that it firmly connects to simply processed ohmic contacts, which is a feasible structure aimed for photon-spin conversion using gate-defined QDs. Furthermore, we examine the irradiation effects of the transport properties of the proposed structure. As a result, PPC have been successfully suppressed and parallel conductions have not been observed after the irradiation at zero gate voltage. This results indicate that the part of problem in regards to DX centers seems to be solved by this proposed structure. Nevertheless, the demonstrated devices have suffered from semiconductor/insulator interface states and we have not yet achieved the field-induced 2DEG sufficiently stable against the light irradiation under an existence of 2DEG. However, this might be overcome by utilizing Al_2O_3 as the insulator forming by atomic layer deposition with trimethylaluminum treatments after $(NH_4)_2S$ or NH_4OH treatments [8]. Utilizing the modulation or delta-doped 2DEG substrates with a wide spacer layer would significantly improve the mobility.

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