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Charging effects of ErAs islands embedded in AlGaAs heterostructures

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Abstract

Self-assembled ErAs islands were grown on GaAs between a two-dimensional electron gas (2DEG) and a backgate electrode by molecular-beam epitaxy. The islands have overlapping Schottky barriers that form an insulating potential barrier. A TiAu topgate was added by shadow mask evaporation. Thermal activation and charging experiments were employed to gain insight into the electronic properties of the ErAs island systems. In addition the 2DEG was characterized as a function of topgate and backgate voltage.

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Keywords: ErAs; Backgate; GaAs; Heterostructure

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1. Introduction

Two-dimensional electron gases (2DEGs) with backgate electrodes play an important role in nanostructure physics. If a topgate is added different properties of the 2DEG such as wave function symmetry in z-direction, the electron mobility, or the effective g-factor can be tuned at constant electron density. Usually, a GaAs spacer layer grown at low temperatures is used to insulate the 2DEG from the backgate [1,2]. Here we present a novel approach based on overlapping Schottky barriers surrounding nanometer-sized self-assembled ErAs islands. The effective barrier height of the island layers was determined from temperature-dependent transport measurements from the 2DEG to the backgate electrode. Charging effects of the ErAs islands were observed as a function of applied backgate voltage and during illumination with an LED. Finally we characterize the 2DEG mobility and electron density as a function of topgate and backgate voltage.

2. Sample

A schematic of the wafer is shown in Fig. 1. Twenty ErAs island layers spaced by 25 nm of GaAs are sandwiched between a 2DEG and a layer of highly doped Si:GaAs that serves as a backgate electrode. The equivalent of 1 monolayer of Er was deposited for every island layer at roughly 500°C corresponding to an island size of about 3–5 nm according to Ref. [3]. Standard Hall bar geometries were defined by wet chemical etching. The Ohmic contacts (Au/Ge/Ni

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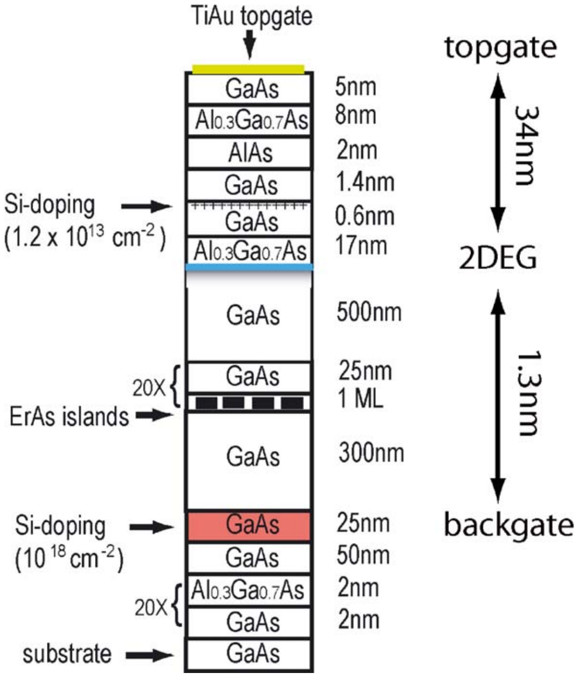

Fig. 1. Layer sequence of the MBE grown wafer. Twenty layers of ErAs islands with overlapping Schottky barriers insulate the topgate from the backgate.

eutecticum) for topgate and backgate were applied and annealed for 10–20 s at 450°C. Breakdown voltages between 2DEG and backgate of up to -7 and over $+7$ V were found. Using a shadow mask technique a TiAu topgate was later evaporated onto the structure.

3. Characterization of the ErAs islands

Temperature-dependent measurements of the current as a function of bias voltage between 2DEG and backgate were performed. Facilitating the well-known relation for thermionic emission across a Schottky junction [4]:

$$J(V) = A^* T^2 \exp\left(-\frac{e\Phi_{\mathrm{B}}}{k_{\mathrm{B}}T}\right)\left[\exp\left(\frac{eV_{\mathrm{bias}}}{k_{\mathrm{B}}T}\right) - 1\right]$$
$$\approx A^* T^2 \exp\left(-\frac{e\Phi_{\mathrm{B}}}{k_{\mathrm{B}}T}\right)$$
$$\times \frac{eV_{\mathrm{bias}}}{k_{\mathrm{B}}T} \quad \text{for} \quad \frac{eV_{\mathrm{bias}}}{k_{\mathrm{B}}T} \quad \text{small,}$$

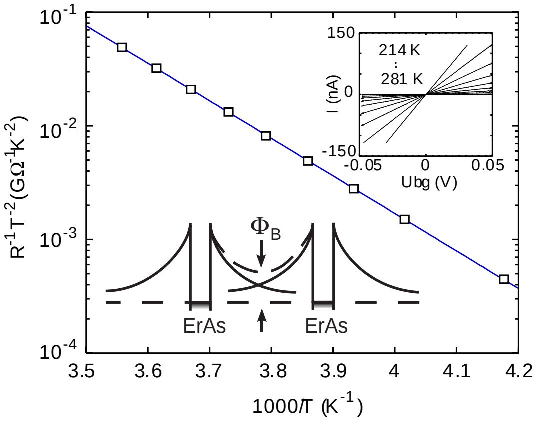

Fig. 2. Arrhenius plot of the inverse resistance 2DEG/BG $\times \mathrm{T}^{-2}$ as a function of inverse temperature. Upper inset: U/I characteristics (raw data) used to determine the resistance. Lower Inset: overlap Schottky barrier height Φ_{B} between two ErAs islands. These minima dominate the value for the effective barrier height. The linear fit through the data points yields a barrier height of 650 meV.

where A^* is the Richardson constant, we determined the effective barrier height of the ErAs-island layers from the slopes of the I–V characteristics around 0 V backgate. An Arrhenius plot of the slopes, as well as the raw data in the relevant temperature range 214–281 K, are shown in Fig. 2. The obtained value for thex effective barrier height across the ErAs island layers is $\Phi_{\mathrm{B}} = (650 \pm 20)$ meV. This method mainly probes the minima between the ErAs islands, because current flow is dominated by the channels with lowest resistance. It should be noted, that our analysis remains valid if two Schottky barriers in opposite bias are considered as would be the case for a solid layer of Er in GaAs. Inplane electronic transport in ErAs:GaAs nanocomposites has also been modeled in terms of hopping of bound magnetic polarons [3]. In our case, where transport occurs perpendicular to the plane, we do not take this effect into consideration.

If the backgate is set above or below a certain threshold voltage, persistent charging of the ErAs islands is observed (Fig. 3). This mechanism was quantitatively studied in the following way. In order to start from a well-defined equilibrium state, the sample was cooled down with the topgate, backgate, and 2DEG grounded. Then the backgate was set to a specified peak voltage and grounded again and the influence on the 2D electron density was measured.

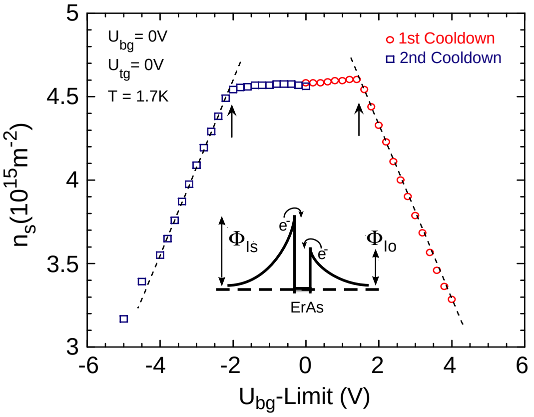

Fig. 3. Electron density at 0 V topgate and 0 V backgate as a function of a previously applied peak backgate voltage at 1.7 K. Inset: model of an ErAs island with different Schottky barrier heights for the substrate Φ_{Is} and overgrowth Φ_{Io} side.

In this way the Hall electron density was recorded at 0 V topgate and 0 V backgate as a function of a previously applied peak backgate voltage (Fig. 3). Above +1.4 V and below −2 V the electron density decreases as a function of peak backgate voltage due to persistent charging of the ErAs islands. By scaling the onset values to the distance between ErAs islands and source electrode (depending on the sign of the bias voltage this is the backgate or the 2DEG) we were able to extract a minimum value for the Schottky barrier height onto the islands. For electron injection from the 2DEG we find a barrier height of $\Phi_{Io} = (510 \pm 50)$ meV and $\Phi_{Is} = (580 \pm 50)$ meV from the backgate. The relatively small discrepancy can be explained by different interface qualities on the substrate and overgrowth side of the metallic islands leading to different Schottky barrier heights. The fact that the values are somewhat smaller than the ones for the effective barrier height can be explained by inhomogeneity among the island layers. Layers containing islands with low Schottky barriers are charged, while island layers with high Schottky barriers are important for the effective barrier height. If the islands are taken to be discs with a diameter of 5 nm the corresponding Coulomb charging energy is about 70 meV, or 10–15% of the Schottky barrier height. All findings are in good agreement with barrier heights reported for Er diodes on GaAs with low-quality interfaces [5] and for measurements across arrays of nanometer-sized W-discs in GaAs [6,7]. Analyzing the linear dependence of the electron density on the backgate voltage (Fig. 3) above threshold in the framework of a capacitance model we find a distance of about 1.3 μm. This is equivalent to the distance 2DEG backgate. We propose the following simple picture to explain these findings: At the threshold values the applied potential slope compensates the Schottky barrier and electrons start to be captured onto the islands. If the voltage is increased additional electrons are trapped onto the islands forming an area charge corresponding to the applied backgate voltage minus the threshold voltage. These electrons remain on the islands when the backgate is grounded again effectively leading to a persistent offset voltage and a lower 2D electron density.

The effects of illumination with a red LED were studied at 1.7 K. Before and after illumination the backgate was insulating with respect to the 2DEG in the GΩ range up to 0.7 V, so no persistent photoconductivity was observed. During illumination the conductivity between 2DEG and backgate increased to roughly 100 nS/mm^2. This behavior is markedly different from the one observed in a similar wafer where persistent photoconductivity was present [8].

4. Characterization of the 2DEG

The electron density and the mobility of the 2DEG as a function of top- and backgate voltage are shown in Figs. 4 and 5. The electron density could be tuned from about 2 to 6.5×10^{15} m^{-2} while the mobility varied from 3 to 12 m^2/V s. These values are comparable to high-quality 2DEGs in AlGaAs heterostructures without backgates, especially if the close proximity of the 2DEG to the sample surface (34 nm) is taken into account. According to Ref. [9] the high-quality crystalline overgrowth can be explained by seeding of GaAs between the ErAs islands. Simulations of the wave function in z-direction with a Poisson–Schrödinger solver[1] show, that the 2DEG is tightly

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[1] The complete structure was calculated self-consistently with a 1D Poisson–Schrödinger Solver, c.1995 by Greg Snider, Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556.

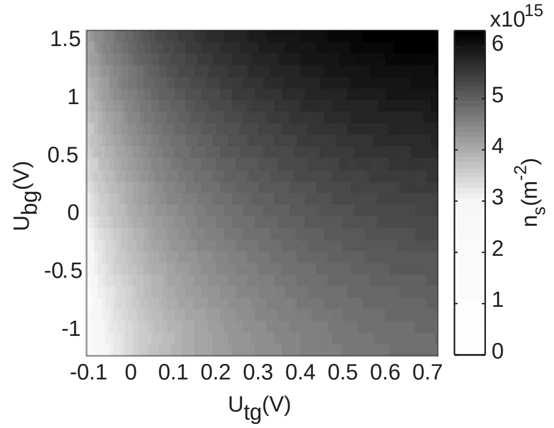

Fig. 4. 2DEG electron density as a function of topgate and backgate voltage at 1.7 K.

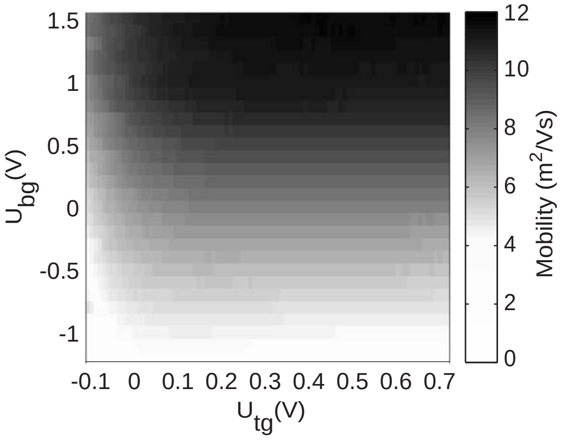

Fig. 5. 2DEG mobility as a function of topgate and backgate voltage at 1.7 K.

pinned to the AlGaAs–GaAs interface and only shifts by about 1–2 nm or 3–5 unit cells of GaAs, indicating that the change in mobility is mainly due to screening effects.

5. Conclusion

We have demonstrated that layers of ErAs islands are an alternative to low-temperature GaAs for insulating 2DEGs from backgates. From thermal activation and charging experiments we extracted Schottky barrier heights of (650 ± 20) meV across the island system and (580 ± 50) and (510 ± 50) meV onto the ErAs islands. Breakdown voltages of up to -7 V and over $+7$ V were achieved, and the high quality of the 2DEG indicates good crystalline overgrowth over the ErAs layers. These properties compare favorably with the ones found in a wafer grown under similar conditions [8]. A notable exception is the absence of persistent photoconductivity. This deviation probably arises from different morphologies of the ErAs islands as a result of slightly different growth conditions. Insulating ErAs island layers could be interesting for many applications in nanostructure physics, especially if local charging is feasible. One could envision e.g. manipulating a 2DEG by a layer of closeby ErAs islands that can be charged in a controlled way with structured gates.

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