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Charge tunable ErAs islands for backgate isolation in AlGaAs heterostructures

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Self-assembled ErAs islands on GaAs embedded between a backgate electrode and a two-dimensional electron gas (2DEG) were grown by molecular-beam epitaxy. The nanometer-sized islands form Schottky barriers with overlapping depletion regions, which insulate the backgate from the 2DEG. From temperature-dependent measurements and charging experiments the effective barrier height between the islands and the Schottky barrier height onto the islands could be determined. In addition, the effects of illumination were studied. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1566793]

Two-dimensional electron gases (2DEGs) based on the Ga[Al]As system are the starting point for a wide range of research. In addition to the option of applying topgates, backgates (BGs) can be a desirable asset. Most traditional approaches for insulating the 2DEG from the BG rely on a GaAs spacer layer grown at low temperatures [(LT) GaAs].[1,2] Here we present an alternative approach based on layers of ErAs islands surrounded by Schottky barriers with overlapping depletion regions. As it turned out this system showed interesting effects in its own right.

The samples under study were grown by molecular-beam epitaxy. A schematic diagram of the layer sequence and the conduction band profile[3] is shown in Fig. 1. The 2DEG is located 34 nm below the surface at an AlGaAs/GaAs interface, separated from the metallic backgate (Si doped GaAs) by 1.3 μm. Sandwiched in between are 20 ErAs layers 25 nm apart. As has been previously reported[4,5] ErAs can spontaneously form islands when deposited on GaAs. The morphology of the islands depends on the growth parameters.[5] In our wafer sequences of 1.5 monolayers (ML) of Er were deposited at 540 °C corresponding to an island size of roughly 5–6 nm according to Ref. 5. High quality crystal overgrowth has been reported for ErAs layers with less than 3 ML due to the possibility of seeding between the islands.[6] All measurements discussed below were done in standard Hall bar geometries with separate ohmic contacts for the 2DEG and backgate. Later a Ti/Au topgate that covered the mesa was added.

At 1.7 K the 2DEG is well insulated from the BG with resistances in the GΩ range up to breakdown voltages of about +6.5 V on the BG, with the Hall bar and leads covering an area of about 0.5 mm^2. The reason why no breakdown was observed for negative voltages up to −8 V is probably depletion of the 2DEG. In a very simplified model the ErAs islands and the surrounding GaAs layers can be viewed as a semiconductor–metal–semiconductor contact where one diode is always in reverse bias. Even though a microscopic model of transport might have to include magnetic polaron hopping[5] it is remarkable that very similar breakdown characteristics (7–12 V) have been observed in macroscopic ErSi$_2$ Schottky contacts on *n*-type GaAs.[7]

Using the BG, we could tune the 2DEG from an electron density of about 4×10^{15} to 6×10^{15} m^{-2} with corresponding mobilities of 7–10 m^2/V s at 1.7 K. As will be discussed later these values and the corresponding BG voltages also depend on the charge state of the ErAs islands. From the linear part of the n_e vs V_{BG} slope a distance of 1.4 μm between the 2DEG and BG could be calculated using a capacitor model. This agrees well with the separation of 1.3 μm predicted from the growth protocol.

Temperature dependent voltage versus current measurements from the BG into the 2DEG were performed to determine the effective barrier height of the ErAs island layers. Current–voltage sweeps between −50 and +50 mV were done from 1.7 K to room temperature. The upper inset in

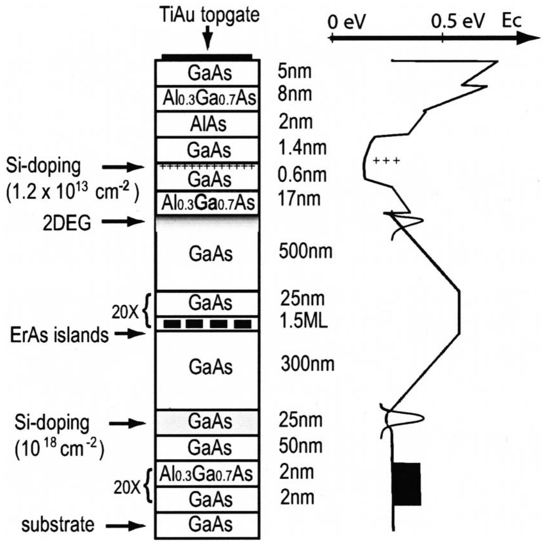

FIG. 1. Left: Layer sequence. Right: Schematic of the conduction band profile based on a simulation with a Poisson–Schrödinger solver (after Ref. 3) (not to scale).

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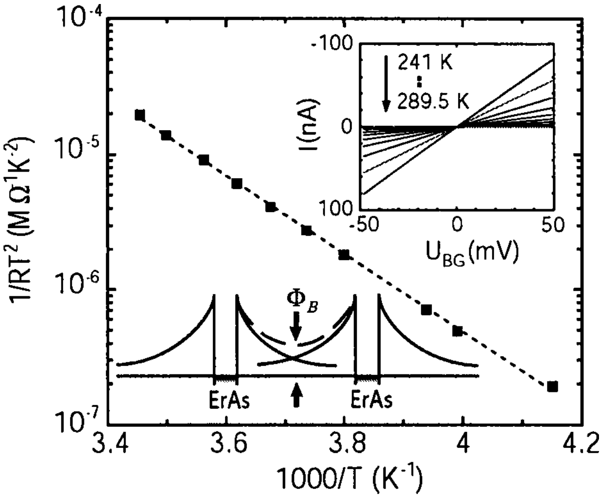

FIG. 2. Arrhenius plot of the inverse resistance between 2DEG and BG. Upper inset: U/I traces (raw data) used to determine the resistance. Lower inset: Illustration of the Schottky barrier minima between islands that are predominantly probed by this method.

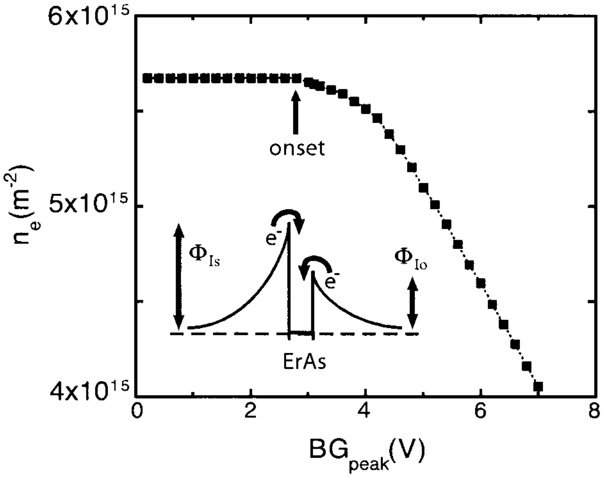

FIG. 3. Electron density at 0 V BG as a function of the previously applied peak BG voltage at 1.7 K. Inset: Model of an ErAs island with asymmetric Schottky barriers resulting from different overgrowth conditions.

Fig. 2 shows the regime for $T > 240\,\mathrm{K}$, where significant changes in the resistance occur. Due to the small range of voltage the slope is basically linear and the effective Schottky barrier height can be determined from an Arrhenius plot (Fig. 2), thus facilitating the well-known relation for thermionic emission:[8]

$$J(V_{\mathrm{bias}}) = A^* T^2 \exp\left(-\frac{e\Phi_B^*}{k_B T}\right)\exp\left(\frac{\mathrm{eV}_{\mathrm{bias}}}{k_B T} - 1\right)$$

$$\approx A^* T^2 \exp\left(-\frac{e\Phi_B^*}{k_B T}\right)\frac{\mathrm{eV}_{\mathrm{bias}}}{k_B T}, \quad \text{for } \frac{\mathrm{eV}_{\mathrm{bias}}}{k_B T} \text{ small},$$

where A^* is the Richardson constant. Because the slopes of U/I traces around 0 V were used this method also yields the correct barrier height if the island layer is viewed as acting like two diodes of opposite bias. The value of (580 ± 20) meV obtained for Φ_B is in excellent agreement with values found in macroscopic Er diodes on GaAs with low quality interfaces[7] and across barriers formed by arrays of nanometer sized W disks.[9,10] Since transport is dominated by channels with low resistance this value is representative of the barrier minima in the overlapping regions between islands (lower inset in Fig. 2).

If high voltages are applied to the BG, the ErAs islands become charged. This effect can be quantified by measuring the Hall electron density in the 2DEG at 0 V BG, then setting the BG voltage to a higher value and measuring the electron density at 0 V BG again. A series of such measurements that plot the electron density at 0 V BG over the previously applied peak voltage is shown in Fig. 3. Onset occurs at 2.8 V followed by a linear decrease in density due to a persistent change in potential that arises from electrons captured onto the ErAs islands. By scaling the onset value with the ratio of the distances between the 2DEG/ErAs layer and BG/2DEG a value of about 1 V is obtained which can be related to the Schottky barrier height Φ_{Io} for charging the islands. This value compares favorably with that of diodes formed at high quality Er/GaAs interfaces.[7] The reason why charging is only observed for positive voltages could be a nonlinear conduction band profile from accidental doping and/or different Schottky barrier heights on the substrate (Φ_{Is}) and overgrowth (Φ_{Io}) side of the islands due to different interface qualities (inset in Fig. 3).

If the sample is illuminated for a few seconds with a red-light emitting diode (LED) at 1.7 K, the resistance BG/2DEG is drastically reduced from several GΩ to about 600 kΩ and the electron density increases. This indicates a lower barrier and results from a reduced number of electrons on the islands. If the temperature is subsequently increased, a rise in the current from the 2DEG into the BG is observed that peaks at about 17.5 K before dropping back to its value at equilibrium as shown in Fig. 4. This is not observed without prior illumination and can be explained by a lowering of the Schottky barrier height (lower inset in Fig. 4). As soon as the thermal energy of the electrons becomes large enough to recharge the islands, the original barrier height is recovered. In order to get an estimate of the energy scales involved we applied an analysis based on thermal activation. From the initial exponential increase on the low temperature side of the peak (upper inset in Fig. 4), where recombination is not

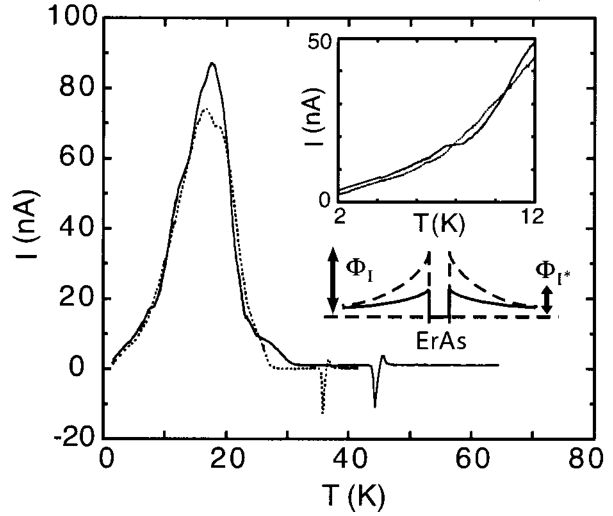

FIG. 4. Two traces of the current between the 2DEG and BG at 5 mV bias after illumination with a red LED (separate cool downs). Upper inset: Exponential increase at low temperatures. Lower inset: Schottky barrier before (dashed line) and after illumination (solid line).

yet dominant, a barrier height of $\Phi_{I*}=(0.3\pm 0.2)$ meV can be extracted using an Arrhenius plot. The peak maximum at 17.5 K and the half width at half maximum correspond to a thermal energy of (1.5 ± 0.4) meV. This value is comparable to a calculated Coulomb charging energy of about 1.5 meV for a metallic disk in GaAs with a radius of 50 nm. Charging energies of the same order of magnitude have been reported in W disks with diameters of 50 nm.[10] If the sample is heated to room temperature a current–voltage dependence that reflects the equilibrium barrier height is observed.

In conclusion, we have demonstrated that ErAs islands are an interesting alternative to (LT) GaAs for insulating BGs from 2DEGs. The mobilities of the subsequently grown 2DEGs are comparable to those in high quality samples without BGs, indicating that crystal overgrowth is not significantly impeded by ErAs islands. From thermionic emission experiments an overlapping Schottky barrier height Φ_B of (580 ± 20) meV between the islands and from charging experiments a barrier height Φ_{Io} of 1 eV onto the islands was determined. Illumination with an LED excites electrons off the islands and reduces the effective barrier height between the islands to roughly 0.3 meV. Recapturing is observed around 17.5 K, corresponding to a charging energy of about 1.5 meV. Very similar observations, with the exception of persistent photocharging, were made on a wafer grown under the same conditions with slightly different growth parameters for the ErAs. The effects mentioned above can be used to tune the barrier height and the 2DEG electron density. This could be of considerable interest especially if local charging is feasible.

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