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Electron gas quality at various (110)-GaAs interfaces as benchmark for cleaved edge overgrowth

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ABSTRACT

We study molecular beam epitaxial growth on the unusual (110) surface of GaAs substrates as prerequisite for cleaved edge overgrown structures. We present the first systematic comparison of the quality of two dimensional electron systems on simultaneously overgrown (110) GaAs monitor wafers with *ex situ* as well as *in situ* cleaved (110) facets. Our study confirms that characterization of the monitor wafer is a valid benchmark for the magnetotransport characteristics of structures grown on cleaved facets. We show that deviating results can be traced back to (110) substrates of lower quality. We also demonstrate that the roughness of the *in situ* cleaved facets is decisive for the quality of the induced electron gas.

1. Introduction

The epitaxial growth of GaAs/AlGaAs on (110) oriented GaAs has attracted attention due to the possibility to realize one- and zero-dimensional charge carrier systems with high precision using the cleaved edge overgrowth (CEO) technique [1]: a conventional multilayer structure grown by molecular beam epitaxy (MBE) along the [001] direction is cleaved in ultra high vacuum (UHV) to create a (110) surface of high purity. This facet is immediately overgrown by a second layer sequence to provide additional potential constriction.

This method enabled the investigation of optical spectroscopy [2,3], lasing [4,5] as well as ballistic transport and related Luttinger Liquid behavior in electron [6–10] and hole [11,12] single-cleave wires. The inclusion of a second quantum well in the first growth step, only separated by a thin barrier from the first one, gave the means to study closely spaced, parallel quantum wires and related tunneling phenomena [13–19]. Additionally, electron systems grown on the cleave facet have been modulated with a superlattice potential [20–23] and with single [24] and double tunnel barriers [25] in the substrate. The unique capability of the CEO method to modulate the potential and reduce the dimension at the same time can even be taken to extremes in double cleave structures, for example quantum dot molecules [26,27] and vertical quantum wires [28]. Furthermore, using the same technique as for GaAs also AlAs [29,30] and InGaAs [31] quantum wires could be realized.

Despite these successes, the implementation of the CEO technique has been only reported by a couple of laboratories worldwide. A crucial prerequisite for this multiple growth technique is high-quality growth on both (001) and (110) surfaces. While two dimensional electron systems (2DESs) with extremely high electron mobilities, exceeding 30×10^6 cm^2 V^{-1}s^{-1} on (001) oriented substrates can be achieved in highly optimized MBE systems, growth on the natural (110) cleavage surface is generally more challenging. The non-polar surface causes an insufficient sticking of the As atoms under standard growth conditions resulting in a poor surface morphology [32]. Furthermore, the Si dopants can be incorporated on As sites and act as acceptors rather than as donors [33]. Therefore, growth parameters need to be adapted and have been investigated earlier [1,34,35,32]. This led to an increase of the arsenic (As_4) partial pressure and to a reduction of the growth rates compared to (001) growth parameters. In addition, the substrate temperature is reduced to avoid thermal desorption from the surface.

The low substrate temperature favors compensation in Si-doped GaAs and AlGaAs layers grown on (110) GaAs, which generally leads to lower electron mobilities [34]. Furthermore, the lower substrate temperature causes higher interface roughness due to reduced surface migration that flattens the growth layers. This issue is especially problematic for optical measurements and can be addressed by growth interruptions where the substrate temperature is temporarily raised for several minutes (the so-called annealing) [36].

The CEO technique was initially established with a simple two-point measurement of a 2DES structure grown on an *in situ* cleaved facet [1]. Later on, a contact design was demonstrated that

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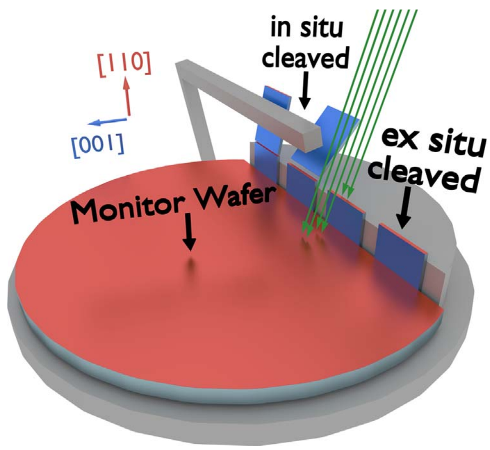

Fig. 1. Three different sample types used for (110) growth in this study, mounted on a specially designed substrate holder: (110) monitor wafer, *ex situ* (in air) and *in situ* cleaved samples. The latter are cleaved using a rotating metal bar in the UHV-environment of the growth chamber. The holder is aligned such that the (001) surfaces of the cleaved samples are shadowed against unwanted material deposition (arrows) during growth.

allows four-terminal magnetotransport measurements [37] on such structures. However, such a direct characterization of the modulation doped structures on the only 100 μm wide cleaved edges, necessary to ensure atomically flat interfaces, is challenging and has not been investigated systematically to date. For this reason, solely a (110) substrate (so-called monitor wafer, Fig. 1) is usually characterized with respect to carrier density n and mobility μ in order to assess the growth quality of simultaneously overgrown CEO structures.

It remains an open question if characterization of the monitor wafer is an adequate benchmark for CEO-structures since substrates and growth conditions are not identical. In addition, it is important to note that the induced 2DES resides in (110) grown GaAs in the first case, while it is usually located on the edge of (001) grown GaAs for CEO-structures (Fig. 2). Since electron mobilities of 2DESs on (001) oriented substrates are higher than on (110) substrates, one could expect higher mobilities in this case as well.

Here, we present the first comparative study of modulation-doped single interface structures (MDSIs) on simultaneously overgrown (110) wafers and *ex situ* [38] cleaved (110) facets. The latter sample type, cleaved in air, allows an assessment of the growth conditions for CEO on a specially designed sample holder (Fig. 1). In a second part, we investigate the 2DES quality of modulation-doped (110) layers directly grown on *in situ* cleaved facets and its correlation to the surface flatness of the cleaved interface. We should point out that only the latter sample type allows a direct comparison to CEO quantum wire samples, as is shown in Fig. 2.

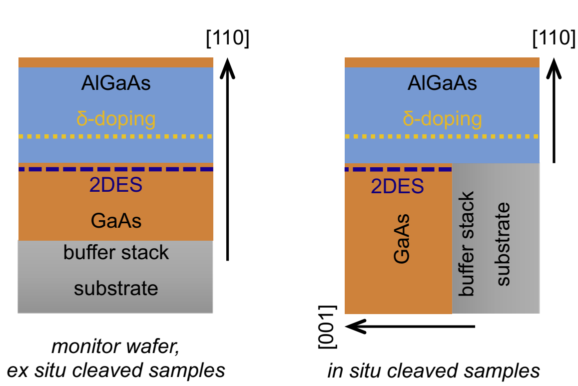

Fig. 2. Growth directions and layer sequences for the sample types introduced in Fig. 1. Note that for monitor wafer and *ex situ* cleaved samples the 2DES resides in (110) grown GaAs, while for *in situ* cleaved samples it is located in (001) grown GaAs, as it is the case for CEO quantum wire structures.

2. Growth of (110)-2DES structures on plane wafers

All samples presented in this study were grown in a high-mobility, modified Varian Gen II MBE setup. For optimized (110) growth conditions, the arsenic (As_4) partial pressure was increased from $7 \cdot 10^{-6}$ Torr used for standard (001) growth to $3 \cdot 10^{-5}$ Torr. Accordingly, the substrate temperature was reduced from 650 °C to 480 °C, as determined by pyrometry, and growth rates were decreased from 2.8 Å/s to 1.6 Å/s.

MDSI structures were grown on semi-insulating (110) substrates of two different manufacturers: *AXT, Inc.* and *Wafer Technology LTD* (WT). The layer sequence is as follows: a buffer layer consisting of 4000 Å GaAs and a 8000 Å thick AlGaAs/GaAs superlattice, followed by a 8000 Å wide GaAs layer, a 300–500 Å $Al_{0.3}Ga_{0.7}As$ undoped setback, a δ-doping layer of Si, 1100–2600 Å $Al_{0.3}Ga_{0.7}As$, capped with 100 Å GaAs.

A 4 × 4 mm sample from the wafer center was contacted each with eight symmetrically placed and annealed In contacts. Characterization was carried out by means of standard magnetotransport measurements in a ^{4}He cryostat, using lock-in techniques. In Fig. 3 we show the mobility-density dependence of 30 MDSI structures measured at 1.3 K before and after illumination using a red LED.

While MDSIs grown on wafers from the AXT-batch (all with 500 Å setback) and the second and third WT-batch (all with 400 Å setback) show rising mobilities with increasing electron densities, MDSIs grown on wafers from the first WT-batch (300–500 Å setback) are limited to mobilities below 10^6 cm^{2}V^{-1}s^{-1}. This could be linked to crystal defects visible on SEM micrographs (after growth), which could be found only for this wafer batch. We point out that no difference between the different wafer batches could be detected by means of optical microscopy.

We note that a record mobility of $6.04 \cdot 10^6$ cm^2 V^{-1} s^{-1} on (110) surfaces at a density of $3.75 \cdot 10^{11}$ cm^{-2}, measured after illumination, could be reached with a wafer from the second WT-batch (growth D160202C, compare Fig. 7(d)).

In addition, we tested the impact of different annealing periods before setback growth on the 2DES quality. As mentioned in Section 1, such annealing interruptions were previously introduced to reduce interface roughness for optical measurements. Comparing the density and mobility values of the first three structures shown in Table 1, we observe no appreciable change by implementing a growth interruption of 10 min (without raising the growth temperature). This means, in contrast to high mobility (001) structures, the 2DES is not

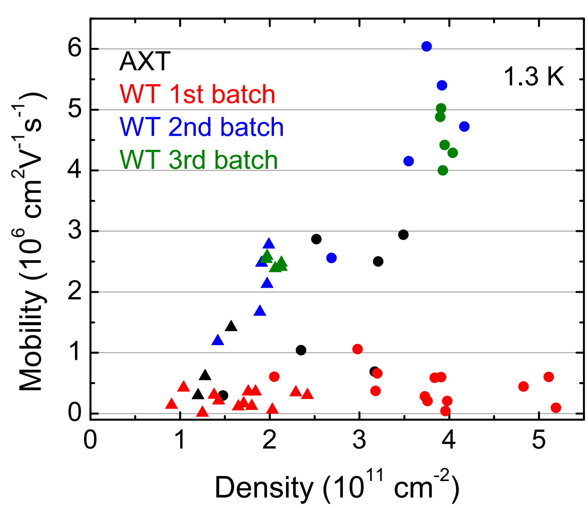

Fig. 3. Mobility-density dependence of MDSI structures grown on (110) wafers from four different batches. Triangles and dots mark measurements before and after illumination respectively. (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)