8 Summary

> Causas rerum naturalium non plures admitti debere, quam quae et verae sint et earum phaenomenis explicandis sufficiant.
>
> *(Sir Isaac Newton, Pricipia Mathematica)*

8.1 Introduction

Real life research projects frequently follow a less than straightforward evolution as planning is adjusted to reflect new discoveries and practical limitations.[1] This can result in a thesis that presents itself as a smörgåsbord of different results and insights with less clear structure than one might hope for. The purpose of this summary is to collect the salient points and put them into perspective.

8.2 Technology

I have demonstrated that local anodic oxidation (LAO) with an atomic force microscope (AFM) can be performed on a variety of GaSb and InAs surfaces, including those grown by metal-organic vapour phase epitaxy (MOVPE), with a performance comparable to that reported for other III-V semiconductors [1, 2]. The technique does meet the expectations in terms of versatility and attainable resolution, with a minimum lateral feature size of less than 30 nm, but is marred by two significant limitations: On the one hand, despite considerable

[1] In fact, one of the lessons I have learnt in the course of the present research is that it might not be wise to resist this process too much.

efforts to improve reproducibility, the results are not very reliable. With sufficient care it is possible to produce highly uniform patterns several square micrometres in size, but the success rate remains disappointingly low. On the other hand, the anodization is limited to the surface of the sample, extending less than 20 nm into the substrate, and modifications with a high aspect ratio are unachievable.

It is possible to avoid this restriction by using LAO to pattern an etch mask instead of directly modifying the semiconductor sample [3], and I have shown how this approach can be implemented on GaSb using an aluminium mask together with a silicon dioxide spacer layer to avoid detrimental reactions of the developing etch with the substrate. The resulting mask can be used directly as a stop layer for a plasma etch process. Then, however, much of the simplicity of the AFM lithography process is lost and it has to compete directly with more reliable conventional pattern transfer techniques such as electron beam lithography (EBL).

8.3 Solid State Physics

InAs–GaSb double heterostructures (DHETS) containing quasi-two-dimensional sheets of both holes and electrons that have been patterned with a regular array of antidots with a period smaller than the electron mean free path exhibit commensurability features in the perpendicular field magnetoresistance similar to those observed in unipolar systems [4]. These features can be attributed unambiguously to the commensurability of the electron cyclotron orbit with the antidot lattice: even though the hybridization between the electron and hole levels breaks up the non-interacting Fermi contours and leads to more complex orbits, electron-like orbits remain possible via magnetic breakdown. The effect of the commensurability on the resistivity can be demonstrated from a semiclassical simulation of electron orbits by means of Kubo's formula. A more intuitive explanation is afforded by the 'pinning' of suitably sized orbits around antidots.

One idea underlying the project discussed in this thesis has been to use LAO to create such potential modulations on InAs–GaSb DHETS. The Fermi level at the InAs layer of DHETS with a thin GaSb cap is known to be highly sensitive to surface states, and preliminary experiments with wet etched antidot patterns have suggested that a complete removal of the cap layer is not needed for creating a strong modulation potential. After investigating a considerable number of shallow LAO antidot samples as originally envisaged, it is now clear that a shallow surface modification with the AFM cannot produce a strong enough potential modulation to cause a measurable effect, even if a substantial percentage of the cap layer is affected.

As the behaviour of these samples is dominated by electron dynamics because of the higher electron mobility and the possibility of magnetic breakdown, the effect of the of mobile holes which set GaSb–InAs structures apart from more familiar systems such as two-dimensional electron gases (2DEGS) based on GaAs–$Al_xGa_{1-x}As$ is elusive. Samples with different potential profiles show different behaviour in a parallel magnetic field which is expected to decouple electrons and holes, with commensurability features disappearing for shallow dots that are expected to present an attractive potential to negatively charged carriers. The presence of commensurability peaks in the absence of a parallel field is then attributed to electron–hole interaction. A single electron-rich thin cap sample exhibits at least one novel peak at a magnetic field higher than that corresponding to the commensurability of the electron cyclotron orbit with the period of the potential. Different explanations have been investigated, but it is improbable that the feature is connected directly to the hole gas.

Supplementary magnetotransport studies on close to intrinsic double well structures have shown that the two wells behave essentially as two independent DHETS conducting in parallel for well distances above 100 angstrom. For smaller barrier widths, there are circumstantial signs for a change in the hole levels in the barrier. In no case an asymmetry between the conduction band states in the two wells has been demonstrated.

8.4 Concluding Remarks

Scanning probe microscopes provide an unprecedented ability to manipulate matter at scales ranging down to atomic dimensions for imaging and fabrication purposes. This capability makes them indispensable for many areas of contemporary research, and we will undoubtedly continue to hear of ever smaller devices constructed with the help of SPMs. It is less obvious which rôle LAO and similar techniques have in this development. Despite considerable effort by many researchers over the past years, the reliability of the method is limited, and while the attainable resolution is currently competitive for many applications, there is not much room for improvement. As pointed out in Chapter 2, the range of the interaction between probe and sample is often more critical for the resolution than the size of the probe itself. In the case of LAO, the underlying interaction is a chemical anodization process, and even in the limit of an infinitely small tip the thickness of the electrolyte layer and the scale of ionic diffusion processes put a lower limit on the possible feature size.

Bibliography

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