Chapter 1

Introduction

The present thesis deals with the underlying physics and material science of the transfer of high-quality single crystalline layers of gallium arsenide and various complex oxides onto appropriate handling substrates by a combination of hydrogen and/or helium implantation and wafer bonding. Numerous attempts have been made for many years to develop methods of achieving high-quality thin single-crystalline layers of semiconductor or oxide materials on substrates. As an example, heteroepitaxial growth of GaAs layers on Si was intensively studied, but due to the lattice mismatch of 4.1% a high density (typically $> 10^7$/cm$^2$) of threading dislocation could not be avoided [1, 2, 3, 4, 5, 6, 7]. In 2001 scientists from Motorola reported on supposedly device-quality GaAs epitaxial layers with low dislocation densities, close to that in bulk GaAs crystals of about $10^4$/cm$^2$, grown onto Si by molecular beam epitaxy (MBE) [8]. Epitaxial SrTiO$_3$ (with a 2% lattice mismatch) was used as a buffer layer in order to absorb the effects of different lattice constants between GaAs and Si based on the hotly debated and controversial concepts of a "compliant substrate" [9, 10, 11, 12, 13] which basically assumes that the intermediate layer can almost freely glide on the substrate and adapt the misfit of the subsequently grown epitaxial layer. In spite of an initial world wide publicity, Motorola has decided to stop its activity in this area. The presence of a low dislocation density in the epitaxial GaAs layers has never been independently confirmed and remains highly doubtful.

Layer transfer from a hydrogen-implanted wafer onto a desired substrate by wafer bonding and layer splitting is an attractive approach for materials integration. This approach has first been proposed by Bruel in 1995 [14] for the transfer of silicon layers and termed "smart-cut". It is now commercially used for the fabrication of silicon-on-insulator (SOI) wafers [15, 16, 17]. The substrate from which the implanted layer is split can be re-used, and a good thickness uniformity (in the 5 nm range) of the transferred layer is achieved by implantation. However, layer splitting can only be achieved if appropriate implantation conditions, specific to each material, are employed. Whereas layer splitting of silicon is now routine, and works for a relatively large range of implantation conditions, for many other materials there appears to exist only a narrow window of implantation conditions (dose, dose rate, actual implantation...
temperature due to beam heating) which makes it much more difficult to get reproducible results. This holds also for GaAs, one of the main materials investigated in this thesis.

A first attempt to transfer GaAs layers onto Si by layer splitting was reported by Jalaguier et al. [18], but relatively high splitting temperatures were required (e.g. 400-700 °C). The implantation temperature was not given in this publication. Tong et al. [19] reported that unbonded hydrogen-implanted GaAs wafers showed blistering of the surface after a subsequent annealing step (a prerequisite of splitting when bonded wafers are used) only if the implantation temperature was in a narrow temperature range of 160-250 °C.

When dissimilar materials are used, it is desirable that the splitting temperature is low enough to allow the bonded wafers to withstand stresses associated with the difference in thermal expansion coefficients. Recently, Gawlik et al. [20] proposed a low temperature GaAs splitting approach by two-step hydrogen implantation and wafer bonding. The two-step H-implantation consists of a high temperature (over 100 °C) implantation up to a dose of about $6 \times 10^{16} \text{H/cm}^2$ followed by a low temperature implantation (below 100°C) step up to the total retained dose of $2 \times 10^{17} \text{H/cm}^2$.

Application of the layer splitting approach for complex oxides is also an attractive alternative to fabricate thin single-crystalline oxide films with precise sub-micron thickness on any substrate at low temperatures [21]. Recently, crystal ion slicing (CIS) has been used to fabricate films of magnetic garnets and ferroelectric crystals [22, 23, 24]. The CIS process allows the formation of freestanding single-crystal micrometer-thick films with preserved domain structure. The technique relies on energetic (MeV) He$^+$ ion implantation to generate a buried damaged sacrificial layer. This layer is found to preferentially etch upon immersion in a suitable etchant, ultimately resulting in microns-thick films separated from the parent substrate.

This dissertation consists of five chapters. Following this introductory chapter, Chapter 2 will present the concepts, key features and main advantages of the layer splitting approach. Ion implantation represents the first step of the process, therefore a review of knowledge of hydrogen and helium implantation in crystalline semiconductors is presented. Since the layer transfer approach involves wafer bonding, which is ideal for realizing material combinations, as one of its key processes, a description of the wafer bonding approach is also presented.

Chapter 3 focusses on the experimental work performed in this study. A more basic description of ion implantation technology, including implantation parameters and the heating effects of ion beams in crystalline materials is presented. Since knowledge of the exact wafer temperature during implantation is an important issue for the layer splitting process, a numerical estimate is presented. Also, the experimental procedures used in this study are described.

Chapter 4 contains the main experimental results of the dissertation. Blistering and splitting of GaAs and complex oxides will be shown. The effects of the implantation temperature are discussed, and the influence of the He+H co-implantation in reducing the splitting temperature/time of GaAs and some oxide materials is demonstrated. Low temperature layer transfer is especially desirable for layer transfer between dissimilar materials such as GaAs and oxides onto silicon. Layer transfer of thin GaAs layers onto Si substrates is demonstrated.
Chapter 5 is devoted to an understanding of the blistering/splitting mechanisms. A thermodynamical model taken from the literature predicts the minimum implanted dose required for blistering/splitting. Two competing growth modes, i.e. blistering with subsequent breaking of the blisters and lateral propagation of micro-cracks are associated with the size and distribution of the platelets in as-implanted wafers and their evolution with annealing. Also, from a mechanical point of view, based on analysis of elastic deformations, the dynamics of the splitting process is described, which also explains the avalanche-like nature of the He and/or H induced layer splitting.