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Smooth p-type GaAs(001) films grown by molecular-beam epitaxy using silicon as the dopant

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Abstract

Atomic force microscopy, Hall effect and photoluminescence measurements were used to investigate the morphological, electrical and optical properties of GaAs(001):Si films obtained by droplet-assisted molecular-beam epitaxy using a peculiar shutter sequence for the delivery of the silicon, gallium and arsenic species. Although silicon is almost exclusively used as a n-type dopant on GaAs(001) substrates, with such growth conditions a p-type character of the GaAs:Si layers was generally detected. The best morphological results were obtained when a single monolayer of gallium and arsenic were alternately deposited and the dopant was evaporated during the gallium cycle, since in that special case no gallium droplets were formed on the substrate, minimizing thus the total roughness of the final surface.

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1. Introduction

Since the advent of molecular-beam epitaxy (MBE), beryllium (Be) has been commonly used to produce p-type GaAs layers. However, this element has several drawbacks [1] (large diffusion coefficient, segregation and clustering at high concentration, large memory effect, low purity and high toxicity), which stimulated the community to substitute it. More recently, solid [2] and gaseous [3] carbon sources have proven their suitability, usually providing doping levels up to 10^{20} cm^{-3} and enabling abrupt doping profiles. However, another attractive option is to exploit the amphoteric characteristic of silicon (Si), with the huge advantage that both n- and p-type GaAs layers might be obtained in the same structure with a single dopant element. Silicon is the usual dopant for n-type GaAs(001) layers and has already been successfully used to produce p-type GaAs layers on high-index GaAs(N11)A substrates (N=1,2,3) where, depending on the growth conditions (mainly the substrate temperature and the V/III flux ratio), the Si atoms can enter the gallium (Ga) or arsenic (As) sites, yielding a n- or p-type GaAs layer, respectively [4,5]. A few years ago, Quivy et al. [6] reported a new way to produce p-type GaAs layers using Si on a GaAs(001) surface that is very important to micro- and optoelectronics because of its two perpendicular cleavage planes. This doping technique is interesting because the Si-doped p-type GaAs(001) layers can be obtained under normal flux conditions just by using a different shutter sequence for the Ga, As_4 and Si materials. The main difference with the usual growth conditions is that several monolayers (MLs) of Ga material containing the Si atoms are first supplied without any incident arsenic (the As_4 shutter is kept closed) in order to simulate a Ga-rich layer where the Si atoms would possibly occupy the As sites, and later the As_4 flux is readmitted (the Ga and Si shutters are closed) to build the GaAs:Si layers. Such a basic sequence can be repeated hundreds of times in order to obtain thicker layers. Hall effect measurements performed on thick doped layers revealed a predominant p character and a low hole mobility, probably resulting from a compensation effect due to a high density of structural defects related to the peculiar growth method.

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In the present work, we report on a complete investigation, by atomic force microscopy (AFM), of the surface of such layers as a function of the relevant growth parameters. Several sets of samples were grown at different stages of the basic growth cycle and analyzed by AFM to investigate their morphology. Photoluminescence (PL) and Hall effect measurements were carried out on the samples that yielded the best morphological results in order to check their optical and electrical properties.

2. Experimental details

All the samples were grown in a Gen II MBE system on top of epi-ready semi-insulating GaAs(001) substrates. As a reference sample for our study, we grew a conventional 0.5-μm-thick undoped GaAs buffer at 570 °C followed by a 0.5-μm-thick Si-doped GaAs layer (nominal Si concentration=4×10^{18} cm^{-3}) deposited at 515 °C using 180 sequences of 10 MLs of Ga+Si material alternated with a 15-s-long exposure to an As_4 flux, as described in more details in Ref. [6]. A first set of three samples was grown to investigate how the initial deposition of several MLs of Ga atoms proceeds in the absence of arsenic. After a conventional 0.5-μm-thick GaAs buffer grown at 570 °C, the substrate temperature was lowered to 515 °C and the samples were exposed to a Ga flux in order to receive an amount of material corresponding to 10, 5 and 2 MLs of Ga material without any supply of arsenic. To ensure a low residual amount of arsenic in the growth chamber, the As_4 shutter was closed during 5 s before the Ga was supplied, which was enough to reduce the background pressure by more than one order of magnitude (from 4×10^{-7} to below 3×10^{-8} torr using only a 400 l/s ion pump in the growth chamber). A second set of samples was grown to analyze the morphology of the Ga film as a function of the substrate temperature before exposure to arsenic. Therefore, an equivalent of 10 MLs of Ga material was deposited at 515, 400 and 300 °C on a conventional 0.5-μm-thick GaAs buffer grown at 570 °C. In the last set of samples, several 0.50-μm-thick Si-doped GaAs layers (nominal Si concentration=4×10^{18} cm^{-3}) were grown repeating some of the sequences described above in order to characterize their electrical, morphological and optical properties. Reflection high-energy electron diffraction (RHEED) measurements were carried out to determine the Ga and As_4 flux and to monitor the growth of all the samples. The surface morphology was analyzed in ambient conditions with a Nanoscope IIIa AFM operating in contact mode with a sharpened silicon-nitride tip. Hall effect measurements were performed at room temperature in the van der Pauw configuration, and the optical response of the samples was analyzed by photoluminescence (PL) using conventional lock-in techniques, the 514.5 nm line of an argon laser, a 1.0 m spectrometer and a cooled GaAs photomultiplier.

3. Results and discussion

Fig. 1a shows an AFM image of the reference sample. The surface of the film is not as smooth as when usual growth conditions (i.e. a conventional shutter sequence where the Ga, Si and As_4 shutters are simultaneously open) are used (Fig. 1c), since a large number of oval-like defects are present all over the surface. Such defects were already intensively investigated and are typical of GaAs layers grown with an excess of Ga material [7]. This is confirmed in Fig. 1b, which shows the surface of a 0.5-μm-thick GaAs:Si layer grown with a usual shutter sequence and using growth parameters similar to the ones of the reference sample, except by the fact that the As_4 flux was slightly reduced in order to switch the surface reconstruction from a 2×4 to a 4×2 configuration during the growth, indicating a Ga-rich surface. The same type of oval defects (but with a larger size) oriented along the [−110] direction is also detected on the surface. Another common feature in both samples is the presence of deep holes that contribute significantly to the total roughness of the surface and are also related to the Ga-rich growth conditions as will be shown later. Room-temperature Hall effect measurements showed that the sample of Fig. 1a had a compensated p-type character, whereas the sample of Fig. 1b was also compensated but was of the n-type [6]. Therefore, although the morphology of the surface and the electrical properties of the reference sample are worse than those obtained with conventional p-type dopants and growth conditions, the use of Si together with a different shutter sequence was enough to provide p-type GaAs(001) layers. In the rest of the paper,

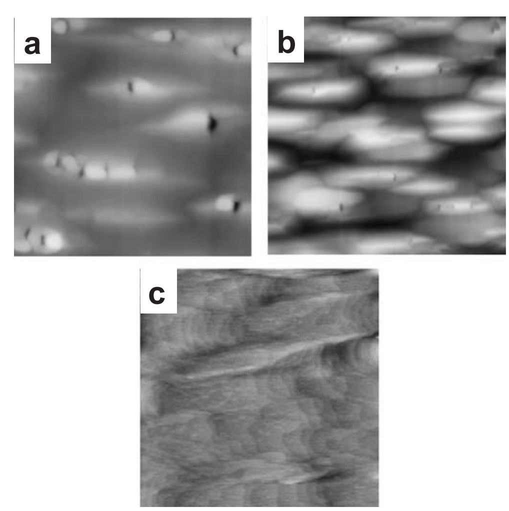

Fig. 1. (a) 2×2 μm^2 AFM image of our reference sample containing 180 repetitions of a basic growth cycle consisting of 10 MLs of Ga material (and Si) exposed to an As_4 flux during 15 s. The total grey scale is 80 nm. (b) 14×14 μm^2 AFM image of a 0.5-μm-thick GaAs:Si layer grown under normal MBE conditions but with a Ga-stabilized surface. The total grey scale is 500 nm. (c) 5×5 μm^2 AFM image of a 0.5-μm-thick GaAs:Si layer grown under normal MBE conditions (with an As-stabilized surface). The total grey scale is 15 nm. All the samples have a nominal Si concentration of 4×10^{18} cm^{-3} and the [−110] direction of the AFM images is from left to right.