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Selforganizing Growth of Nanometer Mesa Structures on (100)-Silicon Substrates

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A self - organizing growth mode of local silicon molecular beam epitaxy is reported. Using ultra-high vacuum compatible microshadow masks epitaxial mesa patterns can be fabricated. The growth process is studied as a function of the orientation of the mask openings relative to the orientation of the substrate. A second parameter is the size of these windows.

Introduction

Molecular beam epitaxy (MBE) is a well-suited method for defined vertical growth on an atomic scale [1,2]. However, for device fabrication the lateral definition of these MBE grown layers is also of importance. This can be achieved by etching of layers deposited uniformly over the substrate as well as by local MBE growth. In the latter case an ultra high vacuum compatible masking technique is required. Micro shadow masks consisting of a structured oxide-nitride sandwich on top of the silicon substrate perfectly fulfill all of these requirements [3] (Fig. 1). The technical details of the fabrication have been reported elsewhere [4]. For the patterning of this sandwich, optical or electron beam lithography in combination with wet and dry etching techniques can be used.
Mesa structures of single crystalline silicon have been grown by depositing silicon through the mask openings at temperatures of 470°C and 600°C on silicon (100) substrates. The resulting geometry of the mesa structures is determined by the mask geometry. But it is not only a one to one projection of this shape. It has been shown that the two dimensional MBE growth is superimposed by additional effects [6]. A preferred formation of (111)-surfaces at the mesa side walls is observed. This selforganizing growth mode is a direct consequence of the anisotropy in surface energy. The maximum size of the (111)-surfaces is limited by the surface diffusion length of the impinging silicon atoms on the (111)-planes. At temperatures of 600°C this diffusion length has been determined to be about 250 nm. In order to study this phenomena in more detail, the mask openings have been reduced to the nanometer regime by using electron beam lithography. A model for the selforganizing growth mechanism to explain the geometrical shape of the side walls has been reported [5]. In this paper we will show that the misalignement of the mask opening relative to the cristallographic orientation of the substrate leads to novel geometries of the mesas.

Experimental conditions

The silicon (100) substrate with the prestructured oxide-nitride sandwich has been fabricated using standard semiconductor technology processes [6]. The mask windows were squares with 1000 nm and 350 nm length, respectivly. The edges were aligned along the [100] as well as along the [110] direction of the substrate. After a cleaning process these wafers are immeditely transferred into the MBE system (Balzers MUM 545). The deposition process starts with a thermal desorbtion of the native oxide on the substrate for 5 min at T=900°C. The base pressure during deposition was less than 10^{-9} mbar. Epitaxial mesa growth occurs within the windows of the shadow masks, whereas amorphous silicon forms on the top of the nitride layer (Fig.1). The growth temperature was 550°C.

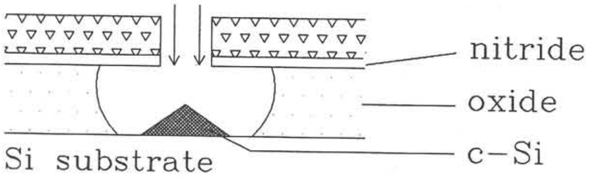

Fig. 1: Schematics for the local MBE growth process by using a micro shadow mask consisting of a oxide-nitride sandwich.

Results

For mask apertures less than twice the diffusion length the mesa islands can take the shape of a pyramid with a sharp tip of less than 10 nm radius (Fig. 2).

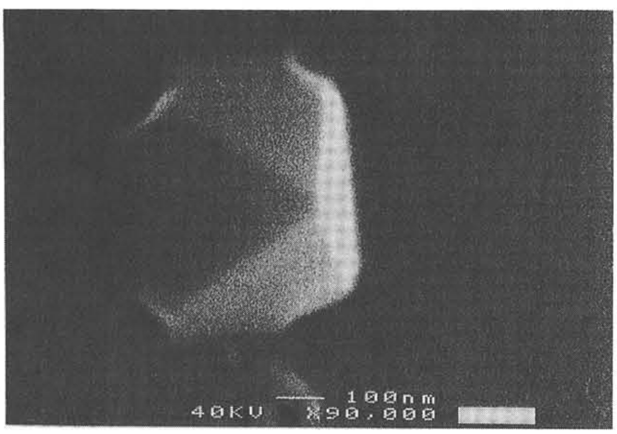

Fig. 2: Scanning electron micrograph of a nano-tip fabricated by the self-organizing growth technique. The mask opening was a square with 350 nm length and the edges are oriented in the [110] directions.

The mask was orientated in the [110] direction, so every base line of the tip is well orientated to form a (111) surface on the sidewalls. At the corners of the pyramid a different crystallographic surface is grown. The center of these surfaces are vertical (100) planes. To study this effect, some of the squares are rotated by 45°. The edges are now orientated in the [100] direction. The resulting mesa grown through this mask is shown in the scanning electron micrograph of fig. 3.

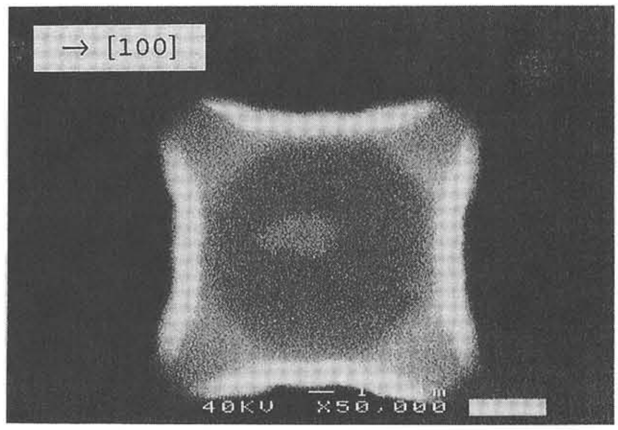

Fig. 3: Scanning electron micrograph of a mesa grown through a square whose edges are orientated in the [100] directions. The mask opening was 1000nm square.

The geometry of this mesa is not a cube as it could be expected. At the corners (111) planes are formed. With increasing height of the mesa, these surfaces tend to become larger whereas the (100) planes are reduced. This selforganizing growth of the (111) planes at the cost of the (100) planes can be explained by the anisotropy of the surface energies of the different orientations [5]. The (111) is the thermodynamically most favourable surface.

Beside this effect it is remarkable that the growth under the mask opening advances further at the corners ([110] direction) than at the edges (([100] direction). This effect can be explained by an anisotropy of the surface diffusion length of the impinging atoms on the (100) substrate surface. The diffusion in the [110] direction (i.e. in direction of the corners) is greater than in the [100] direction (perpendicular to the square side walls). Keeping in mind the 45° rotation, the reduced corners of the pyramid in fig. 2 can also be explained with this assumption because here the corners are in the [100] direction.

Conclusion

The combination of this selforganizing growth mode of single crystalline silicon with selfaligned semiconductor fabrication processes offers the opportunity for a wide variety of future applications in nanotechnology. As an example, in fig. 4 a 4x4 array of nanometer tips is depicted. For practical applications the distance between adjacent tips is limited by the surface diffusion length, i. e. the growth temperature. Furthermore it offers a convenient tool to study one- and zerodimensional systems.

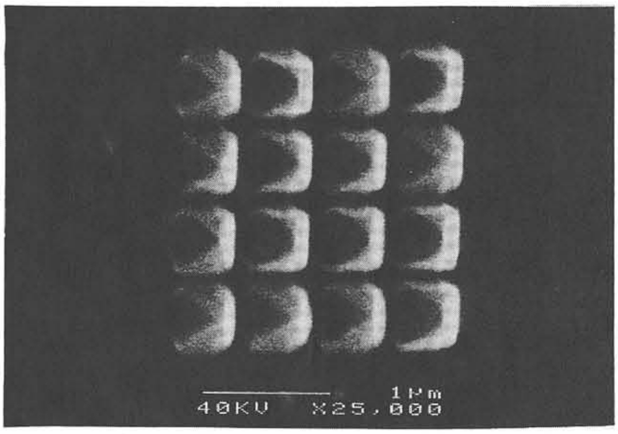

Fig. 4: Scanning electron micrograph of an array of nano-tips.

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