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Atomic resolution observation of GaAs doped with Sn by scanning tunneling microscopy

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Abstract. Substitutional donor Sn_{Ga} atoms in the near surface region below the GaAs (110) cleaved surface were observed by ultrahigh vacuum STM. Surface Sn atoms were observed as localized features, whereas subsurface Sn atoms have delocalized nature with the mean width of 2.5 nm. For an atom, elementary act of surface diffusion was observed and surface diffusion coefficient at room temperature was evaluated.

Development of nanostructure technology for semiconductor devices requires to control distribution of dopants with nm-resolution. A lot of efforts have been done in investigation of electrically active dopants in GaAs by cross-sectional scanning tunneling microscopy [1–5]. Although p-type dopants in GaAs were intensively studied, especially, Be in epitaxial layers [1], Be delta-doped layers [2], Be in modulation-doped structures [3], and Zn in bulk material [1, 4], among n-type shallow impurities only results for Si in GaAs were published [5].

In this paper, we present the first atomic resolution observation of individual Sn atoms (donor impurity) in GaAs.

Tin(Sn)-doped (1×10^{18} cm^{-3}) n^+ GaAs substrates grown by liquid encapsulated Czochralski technique were used as samples for STM imaging. For experiments we used a JEOL4200 UHV STM. The samples were cleaved in situ in an ultrahigh vacuum STM chamber at a pressure of 6×10^{-10} Torr. Obtained this way, atomically flat GaAs (110) surface has low densities of defects, which do not pin the Fermi level at the vacuum-semiconductor interface [6]. Electrochemically etched and backpolished [7] tungsten tips were used. Before loading W tips were treated by hydrogen electron cyclotron resonance plasma at a pressure 3.5 mTorr for 30 min to clean and passivate the tungsten surface [7]. All STM images were taken in the constant current mode with tunneling current 0.1 nA at a sample bias −3 V (filled-state image). The barrier potential was determined for the regions of imaging by measuring current-tip displacement (I-s) characteristics, as well as current–voltage (I–V) characteristics were measured to assure the tip and sample surface cleanliness.

Fig. 1 shows a large-scale STM image on the (110) GaAs surface, where atomic corrugation in direction perpendicular to $[1\overline{1}0]$ is clearly seen, moreover, random white features 1.5–4.5 nm in size are also observed. These delocalized features are very similar to those observed in [5] for Si doped GaAs and attributed to subsurface Si in various subsurface layers. Different subsurface Sn features at the same bias can have different apparent height and width, which were measured by profiling across the features. Mean

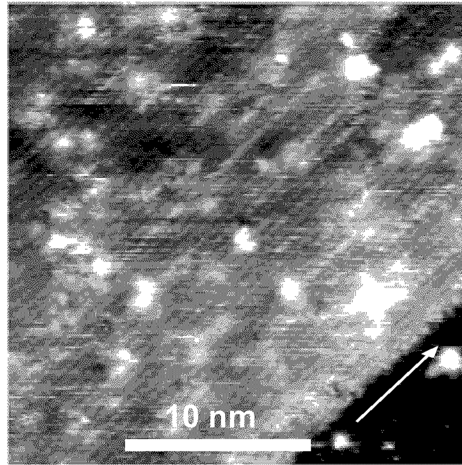

Fig 1. Large-scale image of a cleaved GaAs (110) doped with Sn. Random white (delocalized) features correspond to subsurface Sn donors (I = 0.1 nA, V = −3 V). Arrow shows [1$\bar{1}$0] direction.

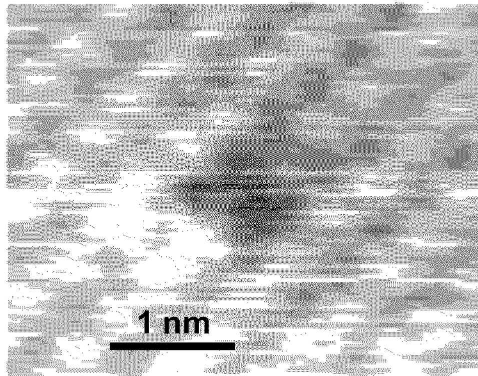

Fig 2. Filled state image of a Sn (localized) atom on the top layer of cleaved GaAs (110) doped with Sn (I = 0.1 nA, V = −3 V).

value of the height for the Sn from the first subsurface atomic layer is equal to 0.23 nm with standard error 0.016 nm, but the width was varied within the range of 1.5–4.5 nm.

At the same time it is possible to observe localized objects on cleaved GaAs (110) surface (Fig. 2). For the Si-doped GaAs (110) surface, calculations indicate [8], that the extra electron of the Si substitutional at a Ga site on the surface is localized around the Si atom, creating a surface Si_{Ga} defect, which was observed as localized feature by STM imaging [5]. We believe that localized features in Fig. 2 corresponds to Sn atom located on the top layer of the surface similar to observation for Si doping in [5].

During our experiments all Sn subsurface atoms were stable, but we observed some additional moveable elements. Figures 3 and 4 illustrate a jump of an atom from, marked by lower arrow place in the figures to that, marked by upper arrow. Both images were

made from the same sample area (as a confirmation of this statement, it should be noted two black features as markers on the top and left-bottom parts of the figures). Besides, one could see new element formation. Instead of white feature (lower arrow, Fig. 3), black feature appears at the same place after 7 min exposure in vacuum at room temperature (Fig. 4). During 7 min of this experiment we made 4 images (first three images were analogous to Fig. 3, showing stable experimental conditions and minor influence of the tip scanning on the feature jump).

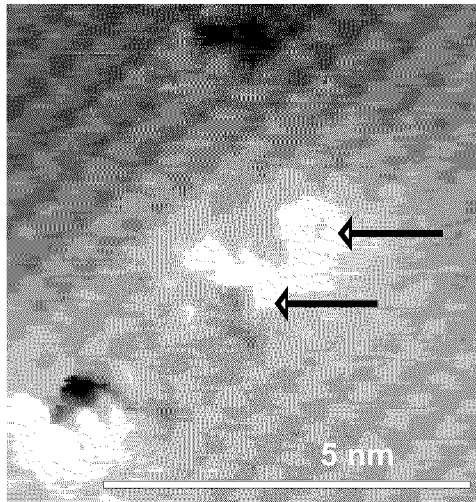

Fig 3. STM image of the GaAs cleaved surface with a movable feature (the starting and the ending places of a jump are indicated by arrows).

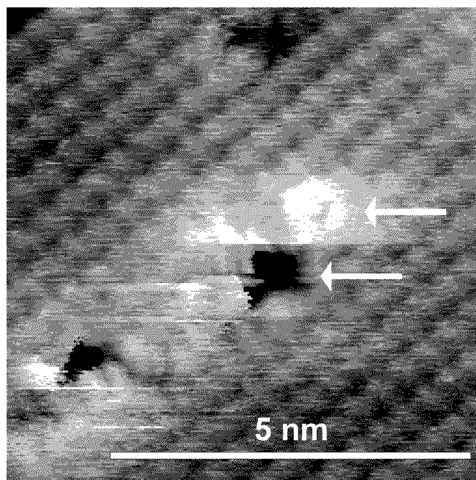

Fig 4. STM image of the area shown in Fig. 3 after 7 min exposure in vacuum at room temperature. The jump of an atom and a new element (black feature) formation are clearly seen.

From the distance between the features (1 nm) and the time period (7 min) we can calculate the "diffusion coefficient" $D = 2 \times 10^{-17}$ cm^2/s, which reflects the elementary act of the surface diffusion at room temperature. We do not know data for surface diffusion of dopants for GaAs (110) at room temperature, therefore, we will try to evaluate the surface diffusion coefficient using data for Si as a dopant. If one extrapolates the data for bulk diffusion of Si in GaAs [9] from high temperatures to 300 K, one can have an evaluation of bulk diffusion coefficient 10^{-21} cm^2/s. Surface diffusion coefficient is 3-4 orders of magnitude higher in comparison with bulk one at the same temperature [10] and have analogous temperature dependence (a decade decrease per 100°C). As a result, surface diffusion coefficient of Si for GaAs (110) should be 10^{-17}–10^{-18} cm^2/s, which is in rather good agreement with the above calculations. Thus, we can conclude that elementary acts of surface diffusion of dopant atoms could be observed at room temperature for reasonable time period.

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