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Regrowth dynamics of InAs quantum dots on the GaAs circular mesa

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Abstract

We report MBE regrowth of InAs quantum dots on GaAs circular mesas, prepared by optical lithography. Because of better strain relaxation, the possibility of quantum dots growth near the lithographic edge is high. Under controlled growth conditions, quantum dots appear only close to the edge. Under these conditions, we discuss the possible influence of crystal orientation to the quantum dots formation, as well as geometrical factors, such as the lateral size of the mesa, and the depth and steepness of the lithographic step. With the full control of the quantum dots formation, we measured the photoluminescence spectrum of the buried dots, as well as the real space image from a CCD camera. The results indicate that quantum dots only form at the edge. Besides the physical location, all the other parameters are quite similar to self-assembled quantum dots formed on planar surfaces.

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Because of the atom-like nature, self-assembled quantum dots (QD) are of great interest as a single photon emitter [1,2]. From early 1990s, this strain-driven phenomenon has been realized and widely investigated on many lattice-mismatched systems, such as Ge/Si [3], InAs/GaAs [4] and InGaAs/GaAs [5]. Despite the nature of random distribution, some techniques are used to "guide" the QD formation. One of them is a QD superlattice [6], in which the underlying layer of QDs serves as the stressor of the upper-level QDs. Another approach is to use lithographic features to seed the QD formation or confine the lateral size of QDs [7]. In this case, usually ultra-high-resolution lithography is required to define the sub-100 nm QDs. In this paper, we will discuss another way to control QDs positioning without the aid of ultra-high-resolution lithography, that is, self-assembled QDs formation on an optical lithographic edge. Kamins

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et al. [8] presented a method of Ge QDs formation on Si pixel lines. It may seem trivial, but this approach can be further developed to incorporate QDs into optical devices [9]. In this paper, we present the research of InAs QDs regrowth on GaAs (0 0 1) substrate. This self-assembled prototype system is mostly widely investigated and unlike the Ge/Si system, we can extract the growth dynamics information using optical methods, besides normal material characterizations.

The GaAs (0 0 1) substrate was patterned with normal optical lithography. Circular features from 2 to 20 μm were transferred to the sample using a wetting etching recipe of diluted H_3PO_4:$H_2O_2 = 1:1$ and photoresist was stripped. After standard solvent cleaning, a wetting etching of diluted NH_4OH:$H_2O_2 = 1:1$ was used to remove a thin layer of GaAs (~40 nm). The sample was then transferred to the MBE chamber for growth. After 1-h high-temperature annealing, a buffer layer of 35 nm GaAs, 1.9 ML InAs were sequentially grown on the substrate at a temperature of 500 °C. At this growth temperature, we typically get an area density of 10 QDs/μm^2, and we can see from Fig. 1a that typically QDs only show up close to the lithographic edge. Here, material migration plays an important role in the QD preferential formation. At our growth conditions, with a substrate temperature of 500 °C and an As/Ga flux ratio of 30, a diffusion length on the order of 1 μm can be estimated. Hence, for the sizes of the circular mesas used, we see no substantial QD distribution in the center area of the mesa. With an increasing of InAs coverage, we noticed that QDs first fill up the edge before they appears elsewhere. For comparison, an AFM image of QDs distribution at a growth temperature of 480 °C is presented in Fig. 1b. We can see that QDs appear almost everywhere, but the density decreases from the edge to the center. So with a diffusion length of tens of nanometers, it is less obvious that the QDs are aligned with the lithographic edge.

Besides the diffusion length, the sidewall of the mesa plays an important role in the QD formation. The InAs material will not only migrate from the top of the mesa but also from the sidewall. To prove this, we apply the QD linear density as a "gauge" to measure the InAs migration. We prepared two samples: sample A with an etching depth of 500 nm and sample B with an etching depth of 1 μm. If InAs does migrate from the sidewall, we expect to see a linear density increase with a shrinking of the mesa sizes. We notice that it is true on both samples A and B (Fig. 2). When both the sidewall and top surfaces are present and

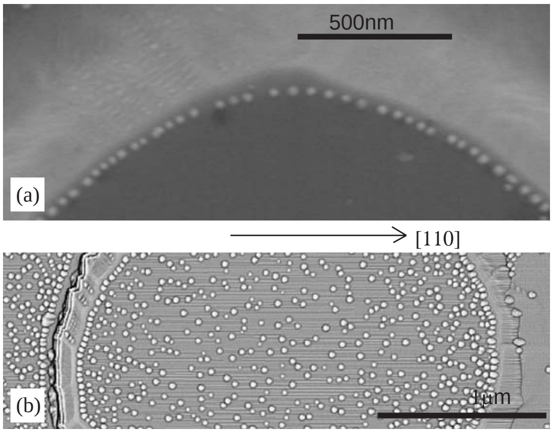

Fig. 1. MBE regrowth on circular mesa structures. (a) The growth temperature is 500 °C. QDs only appear at the lithographic edge. (b) The growth temperature is 480 °C, just 20° lower, and QDs show up on the whole top surface with the area density lower at the mesa center.

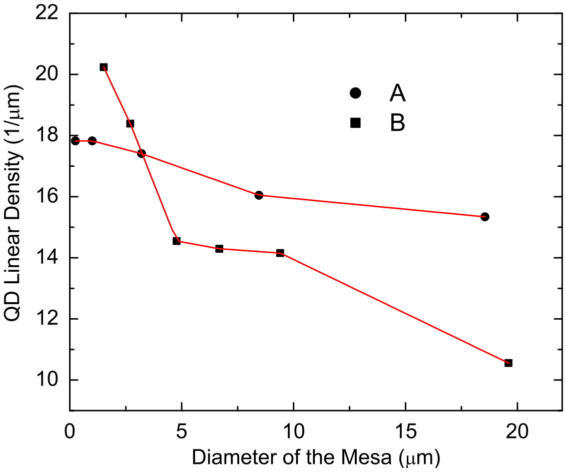

Fig. 2. Average linear density of QDs at the mesa edge. On sample "A", the etching depth is about 500 nm, while on sample "B", the etching depth is 1 μm. On both samples, the linear density slightly increases with the decrease of the mesa diameter.