Control of the Nucleation Density of Si Quantum Dots by Remote Hydrogen Plasma Treatment

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1. Research Target
The application of Si quantum dots as a floating gate to MOSFETs has been attracting much attention because it will lead us to new functionality such as multivalued memory operations even at room temperature [1]. The growth control of nanometer-scale silicon dots with an areal density as large as \( \sim 10^{12} \text{ cm}^{-2} \) on an ultrathin SiO\(_2\) layer is a crucial factor for the multivalued capability of the Si dots floating gate MOS devices. In our previous work, we demonstrated the fabrication of nanometer-scale Si dots on ultrathin SiO\(_2\) layers by controlling the early stages of low-pressure chemical vapor deposition (LPCVD) using a SiH\(_4\) gas [2]. Also we reported that the SiO\(_2\) surface treatment with a dilute HF solution is very effective to obtain dot density above \( \sim 10^{11} \text{ cm}^{-2} \) because Si-OH bonds created on the SiO\(_2\) surface act as reactive sites to precursors such as SiH\(_2\) during LPCVD. In addition, by spatially controlling OH- termination on the SiO\(_2\) surface before LPCVD, the selective growth of Si dots has been demonstrated [3]. In fabricating multiply stacked structures of Si dots in SiO\(_2\), it is very necessary to control Si-OH bonds on the SiO\(_2\) surface by a dry process matching with subsequent LPCVD.

In this work, we demonstrate the feasibility of remote H\(_2\)-plasma pretreatment for controlling the areal density of Si dots.

2. Research Results
The SiO\(_2\) surface was treated with a remote plasma of pure Ar and/or pure H\(_2\). The plasma was generated by inductively-coupling between an external single-turn antenna attached to a 10 cm\( \phi \) quartz tube and a 60 MHz generator through a matching box. The substrate was placed on the susceptor at a distance of 32 cm away from the position of the antenna. The RF power and the flow rate were kept constant at 200 W and 100 sccm, respectively. The gas pressure was changed in the range of 0.1-1.0 Torr and the substrate temperature was varied from 27 to 540 °C. The time of the remote plasma treatment is fixed for 5 s to avoid the reduction of SiO\(_2\) and to minimize plasma damages. The formation of Si dots on as-grown and plasma treated SiO\(_2\) was performed by LPCVD using pure monosilane at 540 °C. During the deposition, the gas pressure was maintained at 0.2 Torr. Figure 1 shows AFM images taken after Si dot formation on as-grown SiO\(_2\) and remote plasma treated SiO\(_2\). In the case of as-grown SiO\(_2\), the Si dot density of \( 6 \times 10^9 \) cm\(^{-2} \) was obtained. When the SiO\(_2\) surface is treated with H\(_2\) plasma prior to LPCVD, the Si dot density is markedly increased up to \( 7 \times 10^{10} \) cm\(^{-2} \). FT-IR-ATR spectra confirm the formation of Si-OH bonds by the H\(_2\) plasma treatment. In the case of Ar plasma treatment in which ion bombardment may occur and induce some damages, the Si dot density is increased by a factor of 10. The results imply that an incidence of atomic hydrogen generated in H\(_2\) plasma to the SiO\(_2\) surface play an important role in the creation of the reactive sites such as OH bonds and hydrides for the Si dot formation. Note that the H\(_2\) plasma treatment subsequent to the Ar plasma treatment provides a very uniform formation of Si dots with an areal density as high as \( \sim 1 \times 10^{11} \text{ cm}^{-2} \). This is interpreted in terms of the improved coverage of OH bonds on the SiO\(_2\) surface as confirmed by FT-IR-ATR measurements. It is likely that weak bonds and dangling bonds created by Ar plasma exposure react efficiently with radicals, ions and excited molecules generated in H\(_2\) plasma.

In conclusion, the combination of remote Ar plasma and subsequent H\(_2\) plasma treatments is very effective to achieve a uniform size distribution of Si dots with an areal density of the order of \( 10^{11} \text{ cm}^{-2} \).

3. Conclusion
We demonstrated the control of the nucleation density of Si-QDs by remote H\(_2\) and/or Ar plasma treatment. The density of Si dots was controlled from \( 6 \times 10^9 \) to \( 7 \times 10^{10} \) cm\(^{-2} \) by changing the substrate temperature and pressure at the remote H\(_2\) plasma process. The combination of remote Ar plasma and subsequent H\(_2\) plasma treatments is very effective to achieve a uniform size distribution of Si dots with an areal density of the order of \( 10^{11} \text{ cm}^{-2} \).

4. Relation of the COE program with the result
These results imply control of Si-QDs nucleation sites utilizing remote plasma treatment is very promising for fabrication of multiple stacked dot structure of Si-QDs.
6. References

7. Published Papers and Patents

① Published Paper

② Proceedings

③ Patents