AFM current imaging for surface oxidized nanocrystalline silicon dots

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Study of electron transport in nanocrystalline silicon (nc-Si) dots has become exceedingly important along with the continuous miniaturization of silicon devices into the decananometer regime. While a considerable effort has been made at investigating average transport properties of the nc-Si dot ensemble, the significance of revealing nanoscopic natures of individual nc-Si dots is also increasing. In this work we report on an atomic force microscopy (AFM) observation of an isolated nc-Si dot embedded in a thin layer of SiO_2 because the nc-Si/SiO_2 structures have frequently been used for the modern devices such as the nano-dot flash memory. The single nc-Si dot was examined by using contact mode AFM, and the experimental results were then analysed using a one-dimensional transmission model of the tunneling current through one nc-Si dot, which takes into account the spherical shape of the nc-Si dot, the substrate orientation and sample biasing.

Preparing the nc-Si dots on the substrate with a very low surface density is one of the most important issues to ensure that only a single dot is involved under investigation. In the present measurements the dot density as low as 3.5×10^9 cm^{-2} was achieved, and a typical dot-dot separation was found from the AFM surface images to be around 100 nm, which is longer than the diameter of the rhodium coated tip of the cantilever. For obtaining the best AFM current images, the tip-to-sample voltages, V_{AFM}, should neither be too low to have measurable current nor be too high to avoid the high-field breakdown of the outer SiO_2 layer. In this work, therefore, the AFM surface and current measurements were carried out in the contact mode at V_{AFM} of 5 and 6 V. The current measured at these voltages agrees well with the current calculated by using our one-dimensional model although a difference between the measured and calculated currents is larger for V_{AFM} = 6V. This is attributable to the leakage current caused by the inhomogeneity in the SiO_2 layer thickness, which may increase under higher applied fields.

Our one-dimensional model also predicts that the tunneling current oscillates with changing the tip position across the entire nc-Si dot, which results from the quasi-local electronic states in the dot. In the present experiments we could not observe any current oscillations, probably because the curvature of the AFM tip is large, and those local fine structures are washed out. Nevertheless, an overall good agreement between the experimental and theoretical results demonstrate that electrons indeed tunnel from the substrate to the AFM probe via a single nc-Si/SiO_2 dot structure, and also the present simultaneous surface & current imaging technique is a powerful tool compared with the conventional I-V measurements.