Imaging the Elastic Nanostructure of Ge Islands by Ultrasonic Force Microscopy

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The structure of nanometer-sized strained Ge islands epitaxially grown on a Si substrate was studied using ultrasonic force microscopy (UFM), which combines the sensitivity to elastic structure of acoustic microscopy with the nanoscale spatial resolution of atomic force microscopy. UFM not only images the local surface elasticity variations between the Ge dots and the substrate with a spatial resolution of about 5 nm, but is also capable of detecting the strain variation across the dot, via the modification of the local stiffness. [S0031-9007(98)06741-6]

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Successes in nanotechnology aimed at the controlled growth of nanoscale structures provide a significant challenge to the existing methods of surface characterization. The physical properties of such structures are intrinsically heterogeneous and vary strongly over distances of the order of several nanometers. Local elastic properties, particularly, play an important role in strained low dimensional heterostructures, strongly affecting their electrical properties and influencing growth and the mechanical stability of such structures [1,2].

Whereas imaging of local electronic properties of nanostructures is relatively well developed (e.g., by electron or scanning tunneling microscopy [3–5]), the physical principles of nanoscale imaging of elastic properties are at an elementary stage. Established methods of microstructural characterization of elastic properties possess either high sensitivity to elastic properties but insufficient spatial resolution (e.g., acoustic microscopy [6–8] or nanoindentation [9]), or adequate resolution but no sensitivity to elastic properties of such rigid materials as semiconductors [e.g., atomic force microscopy (AFM) [10,11] or force modulation microscopy [12]]. The ideal solution would be to combine the advantages of these two approaches, e.g., by detecting ultrasound with an AFM tip. Unfortunately, the AFM cantilever response to ultrasonic vibration in the 1–100 MHz frequency range is very small [13].

Nevertheless, it was recently demonstrated that this problem could be solved using nonlinear detection of ultrasonic vibration [14], which is the core principle of ultrasonic force microscopy (UFM) [15]. UFM exploits the extreme dynamic stiffness of the cantilever [which exceeds the low-frequency (LF) stiffness by a factor of 10^2–10^4] by forcing the vibrating sample to elastically "indent" itself against the dynamically frozen cantilever tip. Owing to the sharp nonlinearity of the tip-surface force-versus-separation dependence $F(z)$, such indentation, repeated with ultrasonic frequency, reveals itself as an additional constant force acting on the cantilever and is easily detected with an extremely force sensitive (at LF) AFM cantilever.

Studies have been reported that show that HF vibration of the cantilever, although relatively weak, could also be detected using a special detection system [16–18] and applied to probe the elastic properties of stiff materials. Nevertheless, these systems inevitably compromise sensitivity to material properties (demanding higher rigidity of the cantilever) with sensitivity to the tip-surface interaction force (demanding lower rigidity) [17]. UFM achieves a reasonable compromise in an unusual way be separating the two cantilever functions (indentation and force detection) in the frequency domain.

In this Letter we report new results on direct imaging using the novel UFM technique, of the local elastic properties of a group IV semiconductor nanostructure system [Ge dots on a Si (001) substrate] with nanoscale resolution. The UFM experiments were complemented by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) studies.

Ge dots were grown on a standard (100) Si substrate following the procedure described in detail elsewhere [19]. The growth was performed in an ambient pressure of 10 Torr at a temperature of about 600 °C. Pseudomorphic growth was observed at thicknesses below approximately 3.5 ML (calibrated by Rutherford back scattering) of Ge resulting in a topographically flat and smooth surface. It is only after this initial flat Ge layer is deposited that the islands start to appear. In this work we will report studies of a sample with 11 equivalent monolayers (including the material in the dots and in the "wetting layer" between the dots) of Ge, containing islands with a narrow size distribution.

The easiest way to realize the UFM mode for imaging elastic properties of Ge islands was to modify a standard commercial AFM [20]. The modification is relatively simple [14,15], and consists of applying an amplitude-modulated ultrasonic vibration (~3 MHz) which is