Measuring the forces during the mechanical vertical manipulation of single atoms at semiconductor surfaces

N. Oyabu[1], *O. Custance*[2], *M. Abe*[1], *and S. Morita*[1,2]
1 Department of Electric Engineering, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
2 Handai Frontier Research Center, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
noyabu@ele.eng.osaka-u.ac.jp

Atomic force microscopy using the frequency modulation detection method [1] (FM-AFM) – also known as non-contact atomic force microscopy [2-4] – allows to probe any flat surface at atomic level in ultrahigh vacuum environment. Nowadays, true atomic resolution images of metallic, semiconductor, and even pure insulating surfaces are routinely obtained with this technique. In FM-AFM, a tip at the free end of a cantilever is oscillated at the cantilever's first mechanical resonant frequency while keeping the oscillation amplitude constant; the main observable is the shift in the resonant frequency, which changes with any variation in the force acting on the tip in a typical timescale of one oscillation cycle. Spatial force spectroscopy performed using FM-AFM allows the quantification of the tip-surface interaction force [5]; and recently, it has been shown the capability of this technique for vertically [6] and laterally [7, 8] manipulating single atoms. All these qualities make the FM-AFM technique a very powerful tool for expanding the nanotechnology horizons.

In a previous work, we showed the possibility of performing vertically manipulations of single atoms at semiconductor surfaces using the tip-surface interaction force only [6]. By applying a soft and well-controlled nanoindentation – allowing the cantilever oscillation amplitude to vary – on specific atomic positions of the Si(111)-(7x7) surface, we were able to remove the Si adatom directly under the tip as well as to deposit a single atom from the tip in a previously created vacancy without any additional perturbation of the nearby local atomic configuration (Fig. 1). In those experiments, however, since the oscillation amplitude was allowed to vary, we could not quantify the interaction forces involved in these manipulation processes.

For this contribution, we have reproduced those results in a different semiconductor surface: the Ge(111)-c(2x8). As it can be seen in Fig. 2, we have been able to remove Ge adatoms from selected surface positions, and to deposit a single atom from the tip in an artificially created vacancy. These experiments were performed keeping the cantilever oscillation amplitude constant, so we could obtain the tip-surface interaction force. From the total interaction force, the short-range contribution – the chemical force between the Ge adatom at the surface and the outermost atom of the tip-apex – can be obtained by minimizing the electrostatic interaction during the experiments and by an appropriate subtraction of the long-range van der Waals contribution [5]. The analysis of the chemical interaction force supports two types of mechanical vertical atomic extraction: "pulling out" and "pushing out". We will show examples in which the tip pulls the Ge adatom out from the surface, characterized by instabilities in the attractive region of the chemical interaction force. On the other hand, we will present examples in which the tip pushes the Ge adatom out from the surface after entering in the repulsive part of the chemical interaction force. We attribute this different behavior to a difference in the "reactivity" of the tip-apex, which in this case relies more on the tip-apex structure and orientation with respect to the surface than in the tip-apex composition. Through the change in the image corrugation before and after the manipulation process, it is possible to determine whether the removed adatom was incorporated directly at the tip-apex – responsible of the resolution in FM-AFM – or nearby it.