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Author(s)	張，家奇
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Abstract

A study of atomic scale mechanics by in situ transmission electron microscopy with a quartz length-extension resonator

Zhang Jiaqi
s1820021

In this thesis, the mechanical properties of Pt and Au nanocontacts (NCs) are investigated by in situ transmission electron microscopy (TEM) observation combined with length-extension resonator (LER) to obtain structural information simultaneously with measuring the spring constant (force constant) and conductance measurements.

The Pt and Au NCs were fabricated with our developed *in situ* TEM holder, which equipped with a quartz length-extension resonator (LER) as a force sensor to examine the elastic properties of atomic-scale materials. The spring constants were determined based on shifts in the resonance frequency of the LER during TEM observation. The mechanical stability of our developed TEM holder was sufficient to allow chains of Pt atoms in the NC to be maintained for at least several seconds. This holder shows high mechanical stability therefore has significant potential with regard to the characterization of nanoscale mechanical properties.

Using our developed holder, we precisely determine the individual bond spring constant in tip-suspended platinum (Pt) monatomic chains using transmission electron microscopy combined with force spectroscopy enabled by a quartz length-extension resonator. We synthesize ~150 Pt monatomic chains consisting of 2–5 atoms. The single bond spring constant at the middle of chain is estimated to be 25 N/m, while that of the bond to the suspending tip is 23 N/m. The chain spring constant shows plateau-like behavior during stretching process, similarly to the quantized conductance. These characteristics including the breaking point are explained by the configurations minimizing the calculated string tension.

In addition, the deformation process and size effect on the Young's modulus of Au nanojunctions with diameter below 3 nm along the [111] direction is evaluated. The narrowest part of the plastic ultrathin nanocontacts becomes thinner under stretch while the angle of the pyramidal shape Au tips still constant. Such deformation process indicates the volume of the nanocontact is not constant and the additional atoms are migrating to the contact area through surface diffusion. The Young's modulus, which is calculated from the spring constant and corresponding geometrical information of the nanocontact, is found to be gradually decrease when the size is reduced. The size dependence of the Young's modulus can be explained by a core-shell model, which shows that the shell of 1 atom layer in thickness has very low Young's modulus (~25 Gpa) and the core has the similar value to the one of bulk [111] Au crystal. These results are in consistent of the observation of surface atom diffusion and indicate that the surface atoms play an important role in the mechanical properties of ultrathin nanomaterials.

Finally, the influence of dislocation on the mechanical properties for Au crystal has been studied. An edge dislocation was found to be appeared and disappeared repeatedly in the Au nanowire when it was stretched. The dislocation would be climbed up during stretching, and the new atom layer will be formed

leading to elimination of the dislocation. The spring constant of the nanocrystal will be largely reduced when the dislocation is formed and recover to the normal value after the dislocation is eliminated.

In conclusion, mechanical properties of atomic scale materials are investigated by our homemade TEM holder. Our result indicate that the atomic scale shows unique mechanical properties than the bulk one. The understanding of mechanics in atomic scale provide essential information for fundamental understanding and applications such as future atomic scale devices and catalyst.

Keywords: structure-dependent electronic properties, suspended graphene nanoribbons, in-situ TEM observation, nonequilibrium phase transitions, restructure