LASER TECHNIQUES FOR BOTTOMS-UP NANOFABRICATION AT THE ATOM SCALE

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Nowadays, it is commonly understood that miniaturization of elementary features in microelectronics devices is approaching the limit in size allowed by conventional technologies, hence pushing the search for novel approaches. The ability to precisely control the matter at the few- or single-atom level is expected to be one of the main ingredients of forthcoming technologies. In fact, accurate space control of elemental species can offer fascinating opportunities in a variety of bottoms-up schemes, including for instance direct deposition of laterally defined nanostructures, surface decoration with regular ordering, precise material doping, molecular functionalization on a local scale. In addition, control of the dynamical properties of the matter can be precious in preventing collateral material damage in any deposition method, thus leading to techniques suitable for soft molecular substrates.

The impressive developments experienced in the last decades by laser techniques have already widely demonstrated their unique ability in manipulating neutral atoms and molecules, leading, for instance, to the reliable realization of Bose-Einstein condensates. We are presently investigating the potential of such techniques in the area of nanofabrication. Key features of laser-based approaches are in the exploitation of electromagnetic radiation as the manipulation tool: radiation is inherently non-obtrusive, can be made species selective, and can be controlled by precise interferometric means, thus offering a great level of flexibility while ensuring the required accuracy.

At the present stage of development, our experimental setup allows for atomic nanofabrication [1] with laser-cooled cesium atoms. Basically, a beam of cesium atoms with sub-thermal temperature is produced out of a modified pyramidal magneto-optical trap (p-MOT) [2] and, after a collimation stage based on transverse laser cooling, is sent onto a substrate. Close to the surface, atoms interact with a quasi-resonant 1-D standing wave: dipolar forces affect the transverse dynamics of the atoms in the beam, which, according to numerical simulations, is channeled into an array of parallel planes with a transverse size in the tens of nm range. Following a conventional atom lithography scheme [3], the channeled beam can be used to impress a particle-sensitive resist consisting of a self-assembled alkanethiol layer grown on gold. Subsequent etching processes lead to an array of nanotrenches 40-50 nm wide, regularly spaced by one half the wavelength of the standing wave (425 nm, in our case). AFM investigations of the produced samples [4] shows that the structure definition is heavily affected by the grain size of the underlying layer, thus limiting perspective exploitations of the method.

Further developments of the technique, aimed at assessing its ultimate potential and exploring alternative implementations, require several steps, the first being direct atom deposition onto atomically flat surfaces. To this aim, we have implemented our apparatus with facilities for UHV substrate manipulation and in-situ sample analysis, accomplished by STM. Results acquired so far demonstrate that a crucial point is played by the interaction between the laser-cooled atoms and the surface, kept at room temperature.

As an example, Fig. 1 (a) shows the STM topography of a nanoline appearing on a HOPG substrate exposed to the laser-cooled cesium beam in the presence of the standing wave: both the direction of the observed structure and its width (in the tens of nm range) are in agreement with the operating conditions of the experiment and the 1-D standing wave configuration, demonstrating the ability of the nanofabrication technique. However, if the exposure dose is reduced, as required when few-atom deposition is concerned, surface physics phenomena, including particle diffusion, coalescence, growth over defective sites, starts playing the dominant role. Cesium nanoislands are frequently observed in this regime, displaying a variety of morphologies ranging through elongated features to isolated nanostructures, the latter being displayed as an example in Fig. 1 (b) referring to a sample deposited in the absence of the standing wave.

Sensitivity on the experimental parameters (e.g., atom flux, standing wave parameters, beam temperature) is being investigated with targeted experiments, aimed also at ascertaining any specific behavior ascribable to the low-temperature regime of the atom beam. The role of the substrate in ruling decoration, deposition and/or penetration of atoms below the surface layer is analyzed as well: preliminary findings suggest that atomic structures are more frequently found close to the surface defects induced by the substrate cleavage process, and this seems to be particularly relevant when laser-cooled atoms are used.

We expect our efforts will help in setting the basis for a more complete understanding of the space control in single- or few-atom deposition schemes, which will be relevant to setup novel approaches using, e.g., atom-on-demand and soft landing methods made available by the progress in laser manipulation techniques.

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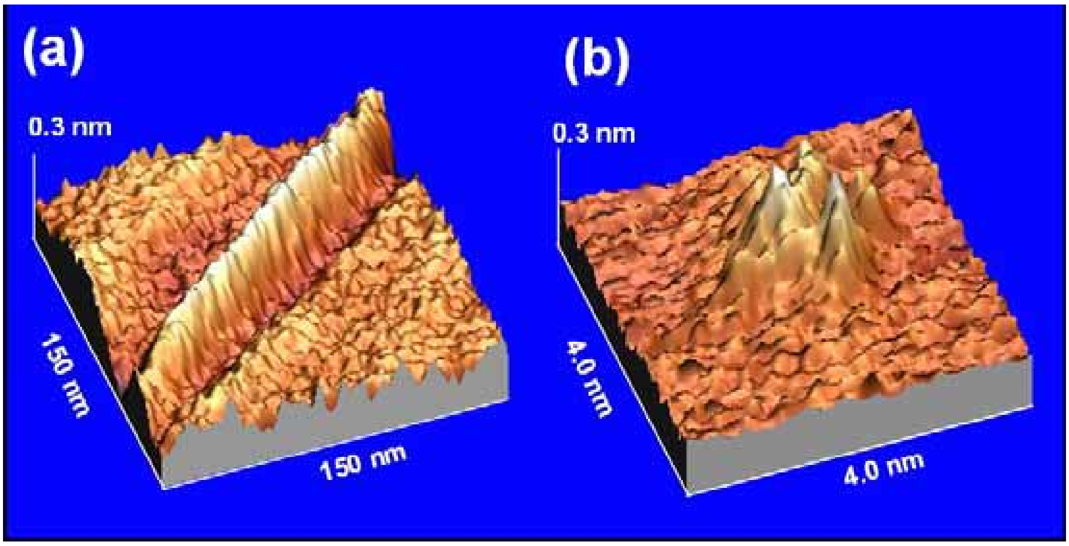

Fig. 1: STM topography of a nanoline (a) and of a nanoisland (b) observed after exposure of a HOPG substrate to a laser-cooled cesium beam with (a) and without (b) the presence of an electromagnetic 1-D standing wave.

References
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3. See, for instance, J.J. McClelland, M. Prentiss, pag. 437 in “Nanotechnology”, G. Timp Editor (Springer-Verlag, New York, 1999).
4. C. O’Dwyer, G. Gay, et al., Nanotechnology 16, 1536 (2005).