Approaching the nanoworld

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ABSTRACT

At the interface of micro and macro world, vision plays a fundamental role in localizing targets and positioning micro- or nanorobots relative to them. Traditionally, far-field optics are used to achieve this task. However, in most practical applications optical diffraction limits resolution to the micrometer-range although image processing may provide us relative accuracies on the order of several nanometers in a few special cases. At ambient pressure, capillary condensation of water vapor severely hampers reproducible and reversible manipulations of micrometer-sized or smaller objects since the resulting adhesive forces between tool and object easily exceed the object's weight. The size of objects also dictates the useful dimensions of sensors and actuators and generally necessitates integration of several sensing and/or actuation functions into a single device. To overcome above mentioned difficulties in accessing the micro and nano world, sensing and actuating principles derived from scanning probe microscopies such as atomic force or optical near-field provide us with the necessary extension of the capabilities offered by traditional far-field systems. A fluid environment also prevents those hard-to-control effects of capillary forces.

1. TOWARDS THE NANOMETER SCALE

Historically, two fundamentally different approaches have been followed to reach the nanometer-world (Fig. 1): engineers adopted a top-down strategy, i.e. by starting from structures and principles well established in the macro-world they ventured into the nm-range via successive cycles of miniaturization. Chemists, on the other hand, naturally adopted a bottom-up strategy as they progressed from synthesizing simple compounds consisting of just a few atoms to current macromolecules. Yet, in contrast to engineers whose techniques were always geared towards individual objects chemists generally found themselves restricted to handling extremely large ensembles of identical individuals ($6*10^{23}$ = 1 mol). Between these two man-made strategies nature appears to have evolved concepts to handle both nano-individuals and "chemical" ensembles as exemplified by biological systems. In fact, most complex functioning nanosystems, i.e. machine-like structures « 1 µm, are of biological nature, such as linear and rotational molecular motors or ion pumps, to name just a few examples with macroscopic analogs. With this observation in mind it appears logical to consider the underlying working principles of those existing nanosystems as guidelines for our attempts of creating man-made nanostructures.

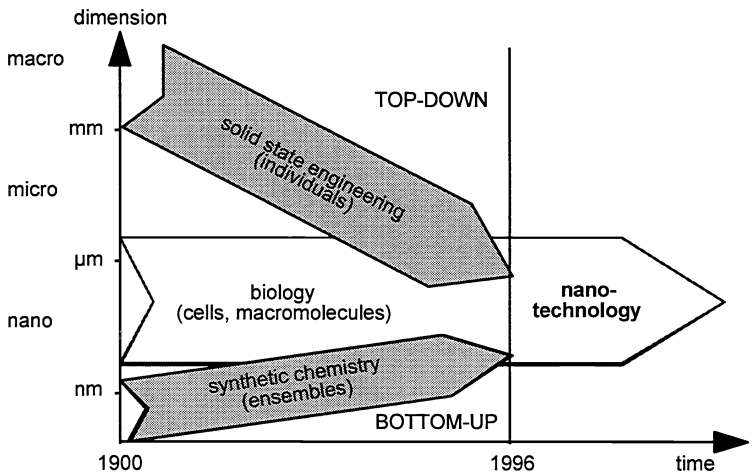

Fig. 1. Approaches to the nanoworld.

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On the nanoscale forces other than gravity play a fundamental role. The majority of interactions between individual sub-micron particles or a particle and a tool may be grouped into three categories. First, Coulomb forces between charges give rise to electrostatic interactions. Unless screened by a medium of high dielectric constant Coulomb forces are strong and long-range compared to the other two categories. Second, polarization forces arise when a particular object is subject to induced dipole moments generated by electric fields of charge distributions around it. In a liquid environment such forces are always present. The third category of forces is of quantum mechanical origin and comprises such diverse effects as repulsion due to the Pauli exclusion principle or covalent (chemical) bonding. They are very short-range, typically 0.1-0.2 nm. One should note, however, that this classification is based on the physical origin of forces rather than common descriptions of interactions - van der Waals forces, for example, cannot be assigned to a single category unambiguously.

With regard to reproducibly manipulating sub-micron objects contact forces are of particular importance. The ratio of object-substrate versus object-tool adhesion determines whether an object can be successfully picked-up, set-down, and finally separated from the manipulation tool. At ambient pressure a large contribution to adhesive forces stems from capillary condensation of water vapor around the contact region. Fig. 2 demonstrates the increase in adhesion with higher relative humidity. A standard microfabricated pyramidal silicon nitride tip at the end of a cantilever as used in atomic force microscopy (typical parameters: tip length 3 μm, tip radius 20-50 nm, angle 70_) was brought into contact with a clean atomically flat mica surface. The force required to pull the tip off the surface, i.e. the force when the cantilever snapped back, was measured with an atomic force microscope (AFM) operating in a controlled humidity atmosphere. A hydrophobic Teflon-like coating on the tip proved to be an effective means to prevent an increase in snap back force with rising relative humidity[1]. In liquid even uncoated tips show very small adhesion[2] because capillary condensation is absent and Coulomb and polarization forces may be controlled via the medium's ionic strength. Obviously, operating in vacuum also alleviates the problem of capillary condensation and successful pick-and-place manipulations to create three-dimensional structures have been demonstrated (T. Sato, private communication). However, controlling electrostatic interactions remains difficult.

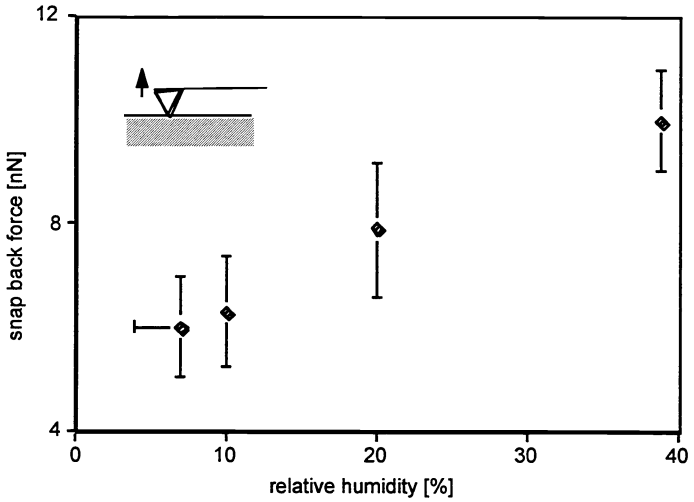

Fig. 2. Influence of relative humidity on adhesion force. Snap back force of silicon nitride tip pulling off a clean mica surface measured with atomic force microscope (inset). Data points averaged from several measurements, error bars indicate spread.

Whereas control over interaction forces determines how reproducibly sub-micron particles can be manipulated and arranged into new structures, visualizing those particles and structures is a fundamental prerequisite for any action involving individual objects in the nanoworld. Electron microscopy has long proved successful in visualizing and resolving nanostructures. Yet, inevitably, the working environment is restricted to vacuum which not only affords us less control over interaction forces compared to liquids but severely limits the possible range of applications for nanomanipulations. In fact, interacting with living biological matter, e.g. cells or intracellular structures would be totally precluded since they require a liquid environment of proper ionic strength. Remains light microscopy as a global vision sensor. At first glance, this technique may appear inadequate for visualizing nanostructurs as the Rayleigh criterion limits resolution d to a few hundred nanometers (Eq. 1; λ wavelength; NAcond, NAobj numerical aperture of condenser and objective, respectively).

$$d = \frac{1.22\lambda}{NAcond + NAobj} \quad (1)$$

Although Eq.1 provides us a measure of how closely two point objects can be spaced in order to still resolve them as two separate entities, we should note that each point object gives rise to a diffraction pattern (Airy disk) where the radius d to the first minimum is given by Eq. 1. Therefore, objects with typical dimensions < d may still be visualized by light microscopy[3] and, most importantly, relative motions of these objects can be detected with sub-nanometer precision[4,5]. This type of super-resolution renders light microscopy a very valuable global sensor for applications at ambient pressure and in liquid. However, absolute resolution, i.e. precise information on the nanometer scale about an object's dimensions or the distance between two objects, remains elusive. To extend the resolution range of light microscopy we propose to complement it with information from local sensors as commonly employed in scanning probe microscopy[6].

2. LOCAL PROBES

Local probes provide us attractive tools to interact with the nanoworld (for an overview see[7]). Presently employed in microscope applications primarily, we believe they could very well be adapted to function in a robotics environment to extend the operating range down to the nanometer scale. Local probes rely on near-field interactions, i.e. they have to be placed within the range of a particular physical interaction mechanism. Depending on the type of interaction, the separation between specimen and probe is adjusted between true contact and a few tens of nanometers. Resolution is a function of the probe's tip radius, its overall shape and how the strength of the interaction varies with distance. Generally, several different interaction mechanisms act on the probe simultaneously. With suitably designed probes these interactions can be measured separately resulting in multi-channel information from the same location. Fig. 3 shows the principle of measuring both nanometer-scale topography and surface potential. The latter is closely related to the work function and thus represents a characteristic material property. To this end, we use an electrically conductive AFM tip (e.g. metal-coated silicon cantilever) and first scan the surface topography. We then retrace the measured topography at a set distance while applying an AC-voltage to the tip at the cantilever's resonance frequency. Thus, the interaction force between tip and specimen becomes modulated and the cantilever oscillates. A feedback circuit adjusts the probe's DC-offset until the oscillation at the excitation frequency vanishes upon which the DC-offset is equal to the local surface potential (Kelvin method).

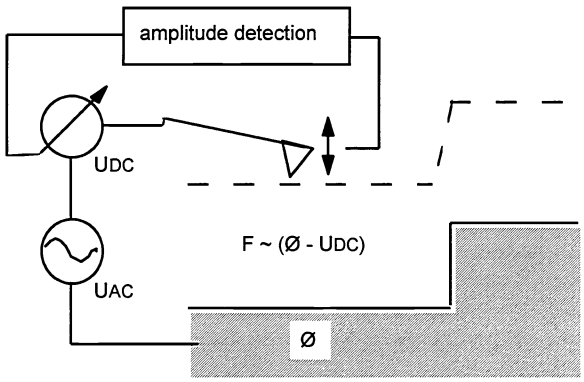

Fig. 3. Set-up to measure topography and surface potential with a modified atomic force microscope probe using the Kelvin method (see text for details).

With this method it is possible to distinguish different materials independent of their topography (Figs. 4-6). In Fig. 4 TaW and PtC layers were evaporated on a glass substrate such that either TaW was on top of PtC (Fig. 4a) or PtC on top of TaW (Fig. 4c). At the resolution shown here the two different structures could not be distinguished from their appearance in surface topography, e.g. size of grains. However, the surface potential provided us a clear material specific contrast with the TaW-layer appearing bright, i.e. with higher surface potential, in both cases (Figs. 4b,d).

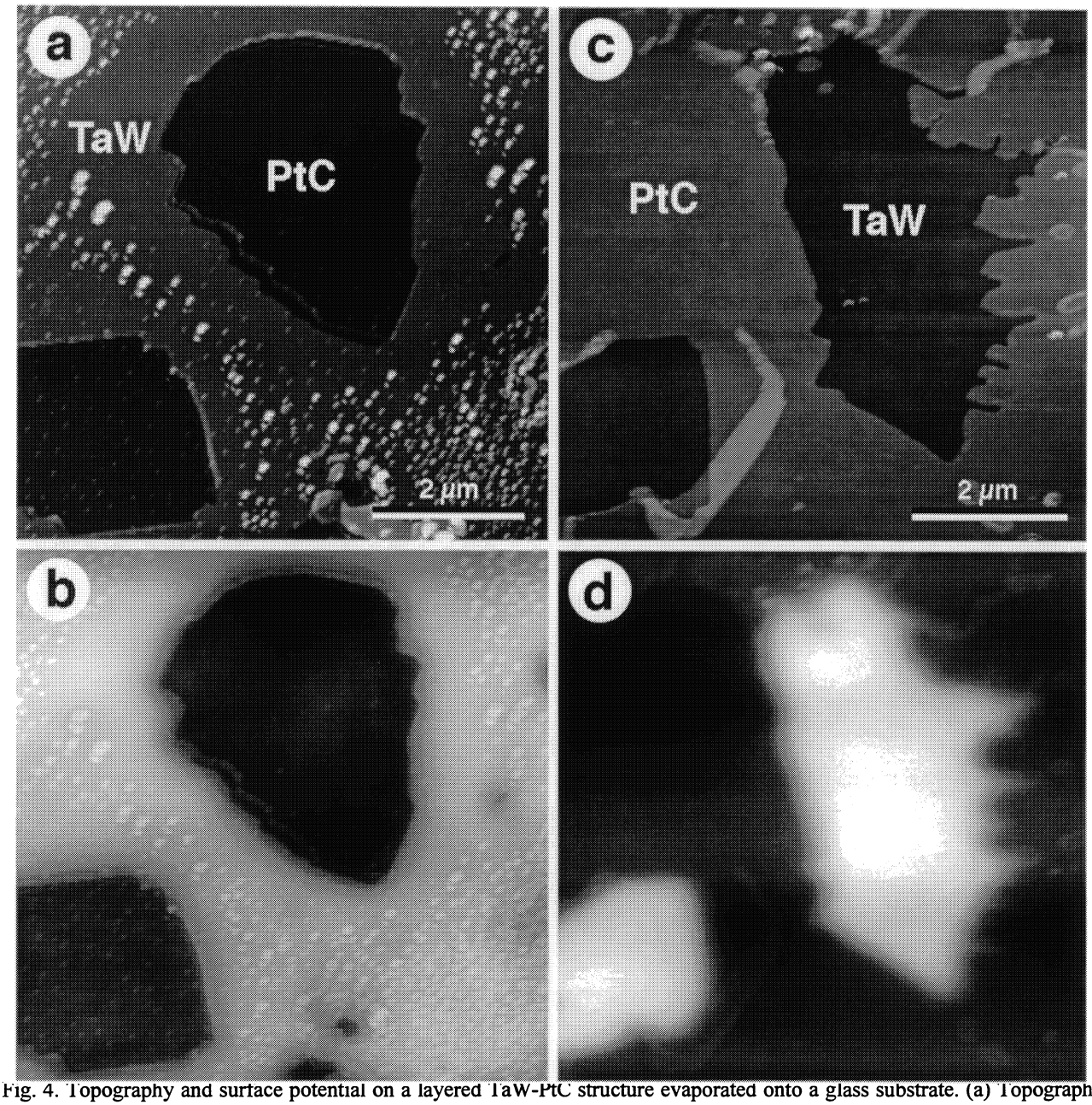

Fig. 4. Topography and surface potential on a layered TaW-PtC structure evaporated onto a glass substrate. (a) Topography of holey TaW film on top of continuous PtC film, (b) associated surface potential measurement. (c) Topography of holey PtC film on top of continuous TaW film, (d) associated surface potential. Layer thickness in both cases (a,c) is 6 nm. Full grayscale represents potential difference of 300 mV in (b,d). TaW film appears bright because it transfers electrons to PtC film and thus becomes more positive in potential.

The same measuring techniques could also be used to detect imprinted potentials on a GaAs-FET (Fig. 5). Currently, we are in the process of applying electrically conducting AFM probes to automatically follow and inspect device structures based on their potential.

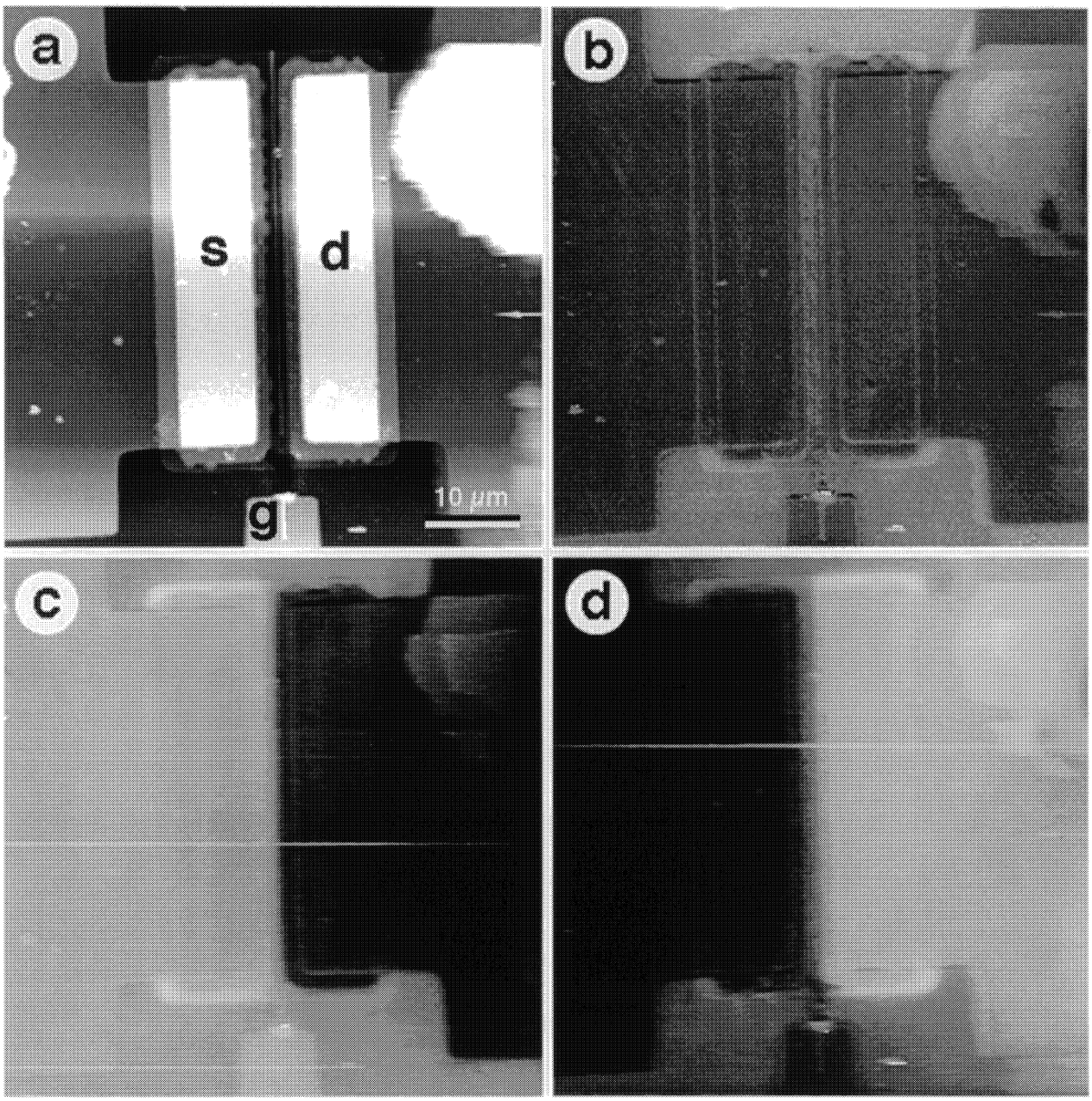

Fig. 5. Topography and surface potential on a GaAs FET. (a) Topography of device with source s, drain d and gate g; full grayscale represents height difference of 1.4 µm. (b) Surface potential of device without applied bias, i.e. contrast is produced by different materials; full grayscale represents 250 mV. (c,d) Surface potential with bias voltage of 1 V applied between source and drain; gate is kept at source potential. Source at positive potential is shown in (c) and at negative potential in (d); full grayscale is 1100 mV in both cases.

Whereas nanometer-resolution is a standard feature of topographic imaging by AFM, hybrid probes as presented above may exhibit different resolutions for their various sensing modes. Fig. 6 displays topographic and surface potential data of a cleaved $Al_{0.15}Ga_{0.85}As$/AlAs vertical cavity laser. Positional information about the transition from n-doped to p-doped region was only available in the potential image. The alternating layers of $Al_{0.15}Ga_{0.85}As$ and AlAs could be detected as a height modulation in the surface topography due to a thin oxide layer which formed in air on the AlAs layers. The material contrast

between $Al_{0.15}Ga_{0.85}As$ and AlAs could be clearly measured as a modulation of the surface potential albeit at a reduced value compared to theoretical calculations because the probe's geometry allowed for electrical interactions over a wider area than the topographic ones which were concentrated on the tip apex.

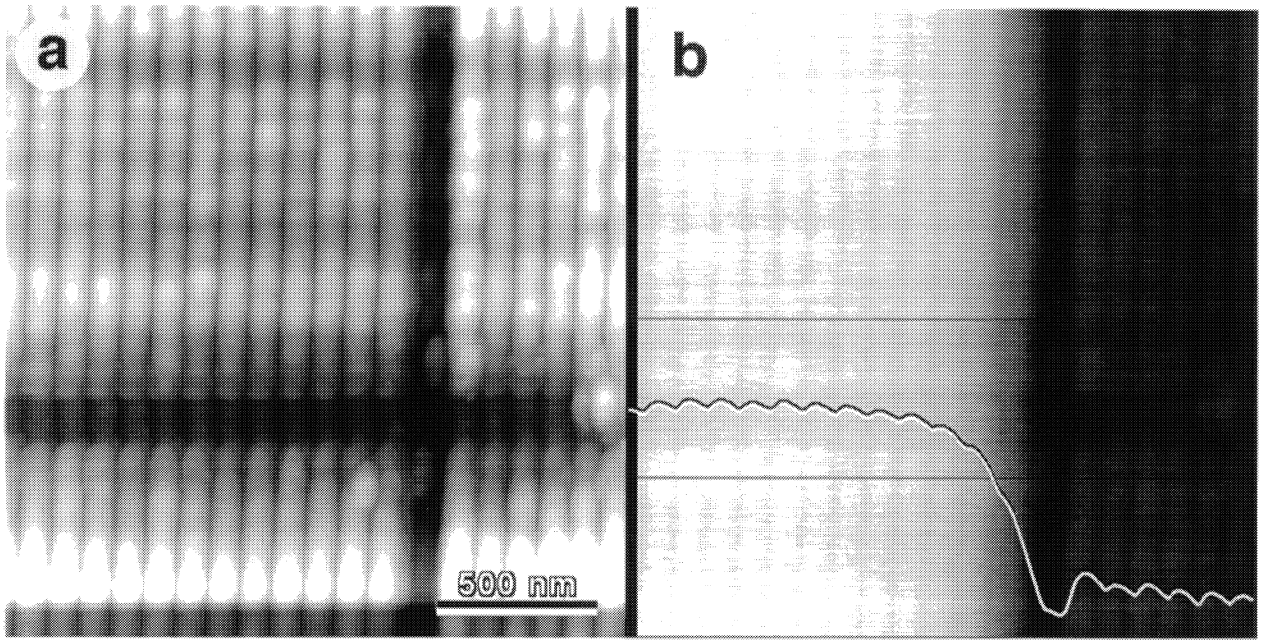

Fig. 6. Cleaved surface of $Al_{0.15}Ga_{0.85}As$ /AlAs vertical cavity laser. (a) Topography and (b) surface potential. The region to the left of the vertical cleft in (a) is n-doped, the region to the right is p-doped. AlAs layers appear higher due to an oxide layer on top of them. The transition from n-doped to p-doped is clearly visible in (b). The alternating $Al_{0.15}Ga_{0.85}As$ and AlAs layers can also be detected as a potential modulation. Full grayscale represents 36 nm in (a). The lines around the potential trace are spaced 120 mV from zero.

3. OUTLOOK

We expect a combination of high-resolution light microscopy, local probe methods, and image processing to become a powerful tool in our quest to visualize, analyze, and manipulate nanostructures. These techniques are particularly suited to operate in liquid and thus will allow us to target chemical and biological systems where advances in nanotechnology are likely to result in an immediate impact.

4. REFERENCES

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