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Electrostatic Force Microscopy, principles and applications to semiconductor materials and devices

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Issued on Scanning Probe Microscopy, the Electrostatic Force Microscopy (EFM) [1] appears as a new and attractive method to explore local electrical properties and bring useful informations, particularly to semiconductor technologists. The aim of this paper is to examine the principles of operation, discuss the observations, illustrate the capabilities of this method in the domain of semiconductors and foresee some future developments.

Generally, Atomic Force Microscopy surface profiles [2] and EFM data can be simultaneously and independently obtained, because the electric effects on the mechanical oscillations are at the second order. The principle of EFM operation is as follows. The SFM like sensor, that must be conducting on the surface facing the examined material, behaves like the mobile plate of a capacitor, the other being the sample. If a voltage difference V is existing between the two plates, an electrostatic force F appears and it is written: $F = 1/2 \mathrm{d}C/\mathrm{d}z V^2$. Besides, if a dc surface charge is electrostatically coupled with the sensor, the Coulomb law gives an attractive force too. These attractive forces induce effects in two ways: they bend the sensor and they change the resonance frequency of the vibrating sensor. Then ω_0 is reduced from $\omega_0 = (k/m)1/2$ to $\omega_0' = (k/m - \mathrm{Grad}F/m)^{1/2}$ [3]. So, when scanning the object, it becomes possible to obtain data about charges [4] and voltages [1]. Since voltage measurements can be reached (nano Kelvin), we shall concentrate mainly on voltage observations. But, now, three questions arise and they concern: the EFM performances, the interpretation of the results and the implementation of EFM.

Since the electrostatic force is a long range interaction and the sensor configuration is complex, the first question is: how to obtain local electrical data and which are the expected performances? The force can be described using numerical simulations [5]. It is shown that a suitable shape of the sensor is required to localise the electrostatic interaction at the extreme end of the sensor — i.e. the tip apex — [6] and that the tip sample distance is a critical parameter which allows to localise the electrostatic interaction on the sample too. Under these conditions, the spatial resolution expected on voltage observations can be deduced [7], then the nanometer scale is related to a tip sample distance lying in the nanometer range. Besides, there is an improvement when detecting the force gradient instead of the force. But, since the force operation is now well established, we shall interest mainly with it.

The second question is the interpretation of the electrical images, or in other terms, the physical significance of the contrasts we can get and how to discriminate between them. For example, if a tip sample voltage V exists and $V = (V_{\mathrm{dc\,applied}} + V_{\mathrm{surface}}) + V_{\mathrm{ac}} \sin \Omega t$, two types of informations are resulting, depending on the observation frequency. First of all, $F_{\Omega} = dC/dz(V_{\mathrm{dc\,applied}} + V_{\mathrm{surface}})V_{\mathrm{ac}} \sin \Omega t$ is depending on both the capacitive coupling dC/dz and the surface potential V_{surface}. Secondly, $F_{2\Omega} = -1/4 dC/dz V_{\mathrm{ac}}^2$ is only related to the capacitive coupling dC/dz. Basing on experimental cases, we can show how to explain the EFM observations.

The third question is the implementation of EFM. Generally, EFM is working under ambient conditions, but up to ultra high vacuum conditions remain possible. Some configurations are examined, it is shown that: (i) we can simultaneously obtain the morphology in the so called "tapping mode" and the EFM data, or (ii) we can use the double pass method on the same line or area. In that case, the tip is retracted from the sample for the electrical observations. The interest of the two methods have to be discussed. In addition, the nanokelvin operation allows to obtain surface voltage variations when making F_{Ω} equal to zero, using a supplementary loop to inject a voltage such as $(V_{\mathrm{dc\,applied}} + V_{\mathrm{surface}}) = 0$.

Then we can enter into the applications, especially in the case of semiconductors. First of all, the detection of the electrical homogeneity in semiconductor material is to be expected, lateral control can be performed using observations on F_{Ω} pictures [8]. Secondly, examination of nano-islands brings useful informations using nanokelvin voltage and force gradient measurements [9], it allows to situate the EFM performances too. Thirdly, observations on structures easily gives the localisation of doped and undoped areas [10]. On semiconductors, the so called capacitive coupling dC/dz is sensitive to the surface bulk capacitor, changing from accumulation to depletion areas is observed. Recent experiments on working LASER structures give access to the control of internal field distributions [11]. Besides, such results are a particularly striking example of coupling three simultaneous observations. They concern: morphology, capacitive coupling and voltage measurements, all things that are important for development of semiconductor technology and for control of modern devices.

We could foresee some directions for future developments of electrical SPM observations. For example, they concern the performance improvements, extension of EFM use and the development of SPM. Based on force gradient detection, the improvement of spatial resolution is under development at our laboratory, first experimental results confirm the expected predictions [6]. At that time, we deal mainly with ambient working conditions but low temperature opens new fields for fundamental physics investigations. Coupling EFM with other electrical methods is also promising. Parallel sensors working simultaneously [12] — like a millipede — open the increase of speed operation and some generalisation of these methods.

In summary, we have shown the principles on which is based the Electrostatic Force Microscopy and the expected performances. Basing on experimental data, we have seen how to interpret the contrasts observed in the experiments. Then we have shown typical observations on semiconductors. We can say that the EFM is now an established method to explore local properties of semiconductor materials, structures and devices, but the field can be widened by new developments.

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References

[1] M. Nonnemmacher, M. O'Boyle and H. K. Wrickramasinghe, *Appl; Phys. Lett.* **58**(25), 292 (1991).
[2] G. Binnig, Ch. Gerber and C. F. Quate, *Europhys. Lett.* **3**, 1281 (1987).
[3] Y. Martin, C. C. Williams and H. K. Wickramasinghe, *J. Appl. Phys.* **61**(10), 4723 (1997).
[4] B. D. Terris, J. E. Stern, D. Rugar and H. Mamin, *J. Vac. Sc. And Tech. A* **8**(1), 374 (1990).
[5] S. Belaidi, P. Girard and G. Leveque, *J. Appl. Phys.* **81**(3), 1023 (1997).
[6] S. Belaidi, P. Girard and G. Leveque, *Microel. and Rel.* **37**(11), 1627, Elsevier ed (1997).
[7] S. Belaidi, F. Lebon, P. Girard, G. Leveque and S. Pagano, *Appl. Phys. A* **66**, S239 (1998).
[8] N. Shmidt, V. V. Emtsev, A. S. Kryzhanovsky, R. N. Kyutt, W. V. Lundin, D. S. Poloskin, V. V. Ratnikov, A. V. Sakharov, A. N. Titkov, A. S. Usikov and P. Girard, *Phys. Stat. Sol.(b)*, **216**, 581 (1999).
[9] A. N. Titkov, P. Girard, V. P. Evtikhiev, M. Ramonda, V. E. Tokranov and V. P. Ulin, *NC-AFM 99 Conference Proceedings*, Sept. 99, Pontresina, Switzeland
[10] A. H. Kenning, T. Hochwitz, J. Slinnkman, J. Never, S. Hoffmann, P. Kaszuba and C. Daghlian, *J. Appl. Phys.* **77**(5), 1888 (1995).
[11] G. Leveque, P. Girard, E. Skouri and D. Yareka, *Appl. Surf. Science* **157**, 251 (2000).
[12] P. Wettiger, *STM'99 Conference Seoul*, July 1999.