The measure of near-surface capacitance in contact mode of scanning probe microscope.

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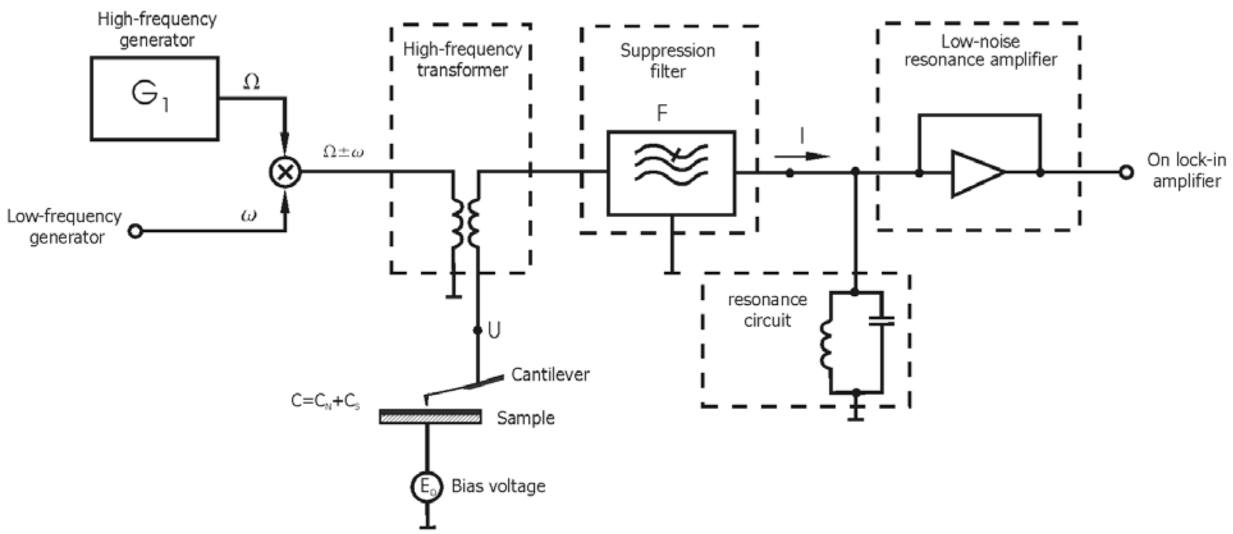
With a development of new techniques in the microelectronic industry, requirements to manufacture of submicron elements have raised. It demands application of new methods of scanning probe microscopy (SPM) for local diagnostics of metric parameters and physical properties of a surface, for study near-surface layers of semiconductor wafers, and also properties of separate elements of semiconductor circuits. Today by means of SPM there is an opportunity of soft interactions of a surface of investigated objects with solid-state probes, registering thus force (electrostatic, magnetic) and thermal fields, a geometrical relief, local hardness, forces of an electric and electrodynamic character, adhesion properties, optical performances of a surface and set of others [1,2,5,7].

In particular, it is interesting to research of dissimilarities of dopant distribution in semiconductor devices alongside with topographical measurements of a geometrical relief. The big interest calls an opportunity of study of parameters p-n junction. For example, the width of a space-charge region depends on applied voltage to p-n junction and visual observation of such dependence is extremely interesting. During manufacture of integrated circuits strictly fixed parameters of doped areas should be ensured, and exact monitoring is necessary. Besides, at production steps of semiconductor wafers and microcircuits diagnostics is important for presence of microimperfections inside near-surface zone etc. Research of all it is possible in so-called capacitance modes of SPM, which may be realized both in a contact mode [3,4] and in a non-contact mode [6,8,9] at registration electrically induced excitation of cantilever oscillation under an force action proportional to the first derivative capacity of a cantilever-sample's system on Z-coordinate position. However, the electrodynamic method realized on the basis of a non-contact mode [6] has not received a wide distribution because of series of deficiencies, basic of which are impossibility of registration derivative $\frac{\partial C}{\partial U}$ and difficulty for interpretation of obtained images. Therefore in the in this paper the capacity technique working on a principle of contact interaction of a probe with an investigated area of a sample will be considered.

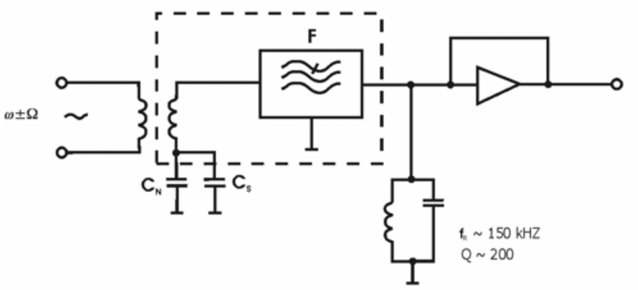
Operation of scanning probe microscope *Solver P47*, *NT-MDT Company*, in a condition of contact measurement of capacity became possible with realization in a construction device of the additional electric circuit figured on picture 1. Two sinusoidal signals with frequencies $\Omega = 48$ MHz and $\omega \approx 75$ kHz from an additional high-frequency generator and from low-frequency generator accordingly, pass through the mixer (pic.1) and there is a voltage $U(t) = A \times [\cos(\Omega + \omega)t + \cos(\Omega - \omega)t]$ on a secondary winding of the transformer**.**

The capacitance (**C**) of a cantilever-sample's system (pic.1) develops of two capacities: capacitance ($\mathbf{C_N}$) investigated near-surface area of a sample which is function of two variables, i.e. time and applied voltage and so-called stray capacitance ($\mathbf{C_S}$), which does not depend on properties of an investigated surface, is defined only by a construction of a device and does not vary during scanning. We shall present capacity of a cantilever-sample's system as two capacities $\mathbf{C_N}$ and $\mathbf{C_S}$, connected in parallel, then the scheme in picture 1 will become (pic.2).

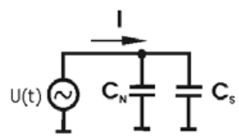
In such resonance circuit (pic.2), for currents with frequencies close to Ω the transformer it is possible to present, as a source of a alternating voltage, and the filter - as the grounding, therefore the equivalent scheme will look like the following (pic.3).



Pic.1 *The scheme of capacitance measuring of a sample in a contact mode of SPM. E_o is a bias voltage on a sample, regulated in a range from –10 V up to +10 V.*



Pic.2 *The equivalent scheme of capacity measurements. Resonant frequency of circuit is about 150 кГц, and Q-factor is about 200.*



Pic.3 *The equivalent scheme of a resonance circuit for currents with frequencies close to* Ω.

Granting, that capacitance of a cantilever-surface's system **($C=C_N+C_S$)** depends on time and applied voltage, the equation describing a current in the given resonance circuit (pic.3) can be written down as follows:

$$I(t)=\frac{d(C\times U)}{dt}=C\frac{dU}{dt}+U\frac{dC}{dt}\ . \qquad (1)$$

The magnitude $\mathbf{C_S}$ is constant, makes about 10^{-11} farad and does not influence change of capacitance **C**. Therefore it is possible to guess, that magnitude of capacitance of a cantilever-surface's system is defined only by value $\mathbf{C_N}$, we have:

$$\frac{dC}{dt}=\frac{d(C_N+C_S)}{dt}=\frac{\partial C_N}{\partial U}\times\frac{dU}{dt}, \qquad \text{so long as}\ \frac{dC_S}{dt}=0\,. \qquad (2)$$

Substituting a value of a derivative $\frac{dC}{dt}$ from (2) in (1) it is obtained:

$$I(t) = \frac{dU}{dt} \times \left[C + U(t) \times \frac{\partial C_N}{\partial U} \right]. \quad (3)$$

At definition of a current through a cantilever-surface's system we shall suppose, that $\frac{\partial C_N}{\partial U}$ does not depend from **U**, i.e. we shall be limited to linear approximation **C_N(U)**. Therefore, it is possible to guess, that capacity's magnitude of near-surface layer of a sample at any moment varies under the law:

$$C_N(U,t) = C_o + U \times \frac{\partial C_N}{\partial U}, \quad (4)$$

where C_o is capacitance of near-surface layer of a sample at zero bias voltage.

Knowing expression for the voltage $U(t) = A \times [\cos(\Omega + \omega)t + \cos(\Omega - \omega)t]$ in the resonance circuit, we shall receive:

$$\frac{dU(t)}{dt} = -A \times [(\Omega + \omega)\sin(\Omega + \omega)t + (\Omega - \omega)\sin(\Omega - \omega)t]. \quad (5)$$

It is possible to receive the law of change of a current in the resonance circuit at any moment from (1), (2) and (5). Thus, we have:

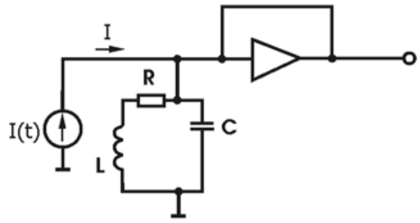
$$I(t) = -A \times (C_N + C_S) \times \{(\Omega + \omega)\sin(\Omega + \omega)t + (\Omega - \omega)\sin(\Omega - \omega)t\} -$$

$$- \frac{A^2}{2} \times \frac{\partial C_N}{\partial U} \times \{(\Omega + \omega)\sin 2(\Omega + \omega)t + (\Omega - \omega)\sin 2(\Omega - \omega)t + 2\Omega \sin 2\Omega t + 2\omega \sin 2\omega t\} \quad (6)$$

The input electrical impedance of suppression filter (pic.2) on frequencies $\Omega \pm \omega$ is small and has resistive character. On frequency 2ω the input impedance has capacitive character and is added to capacity of the resonance circuit. The current with frequency 2Ω = 96 МГц has the same amplitude, as a current with frequency $2\omega \approx 150$ кГц, but is much more strongly suppressed by the filter and does not get in a resonance band of the circuit. Currents with frequencies $\Omega \pm \omega$, $2(\Omega \pm \omega)$ become isolated on the ground through filter **F** (pic.2) and also do not get in a resonance band of the circuit. Thus, it is possible to consider only a component of current with frequency 2ω. Therefore from (6) we obtain expression for a current:

$$I(t) = -A^2 \omega \frac{\partial C_N}{\partial U} \times \sin(2\omega t), \qquad \text{where A is constant.} \quad (7)$$

For currents with frequencies close to 2ω the scheme (pic.2) looks like, figured in picture 4.



***Pic.4** The equivalent scheme of a circuit for currents with frequencies close to* 2ω.

Hence, from (7) follows, that an amplitude of current **I_A** directly proportional to magnitude of derivative capacity of near-surface layer of a sample (**C_N**) on voltage (**U**) on cantilever:

$$I_A \sim \frac{\partial C_N}{\partial U}. \quad (8)$$

Thus, the amplitude value of a current (8) is amplified by the resonance amplifier (pic.1), is processed by the lock-in amplifier and is produced as a picture of distribution of magnitude derivative $\frac{\partial C_N}{\partial U}$ in each point of an investigated area of a surface.

The scanning and registration derivative $\frac{\partial C_N}{\partial U}$ is carried out in a contact mode of SPM. So artifacts of measurement because of capillary effect and a deformation of a relief under pressure in a cantilever-surface's system are probable. Influence of capillary effect considerably can be reduced if scanning to carry out in a controlled helium atmosphere. Pressure should be selected so that the condition $\frac{dC_S}{dt} = 0$ was satisfied, that is obtained by regulation of pressing force of a cantilever to a sample. Besides the degree of an artifact is caused by performances of cantilever (a radius of probe's curvature, a rigidity, quality of conducting coverage) and a choice of scanning conditions. Speed of scanning is selected proceeding from resonance frequencies of the resonance circuit and cantilever, and also - from the appropriate Q-factors.

In capacitance mode of SPM there is a complication [10] concerned with calibration of magnitude of capacity, which may be decided only by the creation of test structures with obviously known parameters, such as the permittivity, a layer resistivity etc. Now operations on creation of similar structures are carried on. For experimental validation of an opportunity of research p-n junction by means of a capacitance method circumscribed above on devices basing electronics and the software of the NT-MDT company, special test samples with different doping level now are developed and manufactured. One of such samples is schematically imaged in picture 5.

Pic.5 *Schematical image of test structure for the contact capacitance mode.*

Test samples may represent the single-crystal silicon wafers doped by boron by means of thermodiffusion up to doping concentration of 10^{20} sm^{-3}, so that alternation of p and n zones was observed. The period of alternation may be in limits from 1 up to 5 microns. After a doping the blocking mask should will be deleted so that maximal planarization of areas with p-n junctions was amounted. Parts of such test sample with different concentration levels have different values of capacity C_N. According to (1), it results in dissimilarity of an amplitude value of a current on given parts.

Using the capacitance mode based on contact scanning, it is possible to register distribution of doping electroactive dopant, amounting thus sensitivity about 10^{-17} farad on a volt. The given technique allows to inspect a doping level within the limits of 10^{15}-10^{20} sm^{-3} with the maximal resolution in a plane of a sample up to 10 нм.

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