CANTILEVER DEFLECTION SENSOR AND USE THEREOF

This invention relates generally to to means for measuring the forces and/or deflections of cantilever type elements, as encountered for example in the field of Atomic Force Microscopy (AFM). The invention further relates to a method and apparatus for determining material properties. In particular, it relates to a dopant profiler based on a scanning probe microscope involving the generation and detection of higher harmonics of an applied electromagnetic field.

BACKGROUND OF THE INVENTION

The Atomic Force Microscope as first known from the U.S. Pat. No. 4,724,318 and further described by G. Binnig, C. F. Quate and Ch. Gerber in Phys. Rev. Letters, Vol.56, No.9, March 1986, pp.930–933, employs a sharply pointed tip attached (to a spring-like cantilever beam to scan the profile of a surface to be investigated. At the distances involved, minute forces occur between the atoms at the apex of the tip and those at the surface, resulting in a tiny deflection of the cantilever. In U.S. Pat. No. 4,724,318, this deflection is measured by means of a tunneling microscope, i.e., an electrically conductive tunnel tip is placed within tunneling distance from the back of the cantilever beam made also conductive, and the variations of the tunneling current are used to determine the deflection. With known characteristics of the cantilever beam, the forces occurring between the AFM tip and the surface under investigation can be determined.

The forces occurring between a pointed tip and a surface are usually described as van-der-Waals, covalent, ionic, or repulsive core interaction forces.

An important aspect of AFM is to accurately determine the deflection of the cantilever. One group of these defection measuring methods is based on coupling the cantilever to another distance sensitive microscope. A combination of the cantilever with a scanning tunneling microscope is described, for example, in the above mentioned patent U.S. Pat. No. 4,724,318. Another approach using an evanescent wave coupling sensor, also known as scanning near-field optical microscope (SNOM) or scanning tunneling optical microscope (STOM), is described by Diaspro and Aguilar in: Ultramicroscopy 42–44 (1992), pp. 1668–1670.

Another group of detecting methods is based on the well known piezoelectric or piezoresistive effect. An example is described in: M. Tortonese et al., Appl. Phys. Lett. 62(8), 1993, pp.834–836. These methods provide detection schemes in which the deflection detector is integrated in the cantilever.

Yet another feasible way of detecting the displacement of the cantilever relies on capacitance sensing and is known, for example, from Joyce et al., Rev. Sci. Instr. 62(1991), p. 710, and Göddenhenrich et al., J. Vac. Sci. Technol. A8(1990), p. 383, and the European patent application EP-A-0 290 648.

By this application as well as from U.S. Pat. No. 4,851,671 methods are known use the changes in the resonance frequencies of the flexible element and higher harmonics thereof to measure its bending. The frequencies are detected either by a quartz oscillator or by a capacitance additionally attached to the cantilever.

The displacement of the flexible element can also be measured by applying optical methods, such as beam deflection or interferometry. The beam deflection method makes use of the length of the lever. Usually, a light beam, preferably produced by a laser diode or guided through an optical fiber, is directed onto the lever. A small deflection of the lever causes a reasonable change in the reflecting angle and, therefore, results in a deflection of the reflected light beam that is measured with bicell or other suitable photo detectors. The beam deflection method is simple and reliable. It is described, for example, by Myer and Amer in Appl. Phys. Lett. 53 (1988), pp.1045–1047. Interferometric methods are described, for example, by Martin et al., J. Appl. Phys. 61(1987), p.4723, by Sarid et al., Opt.Lett. 12(1988), p.1057, and by Oshio et al., Ultramicroscopy 42–44(1992), pp.310–314. As the sensitivity of the SPM can be increased by building cantilevers with ever higher resonance frequencies while trying to maintain the Q factor, a tendency towards smaller cantilevers can be observed. For these cantilevers the above optical methods are prone to failure due to a diminished reflectivity and problems which arise from the limited focus size of a laser beam.

Present day very large scale integrated (VLSI) circuit technology demands an accurate knowledge of the spatial extent, density, or distribution in all three dimensions of the active components (dopants) which are introduced into a base or host material. The most common devices produced by VLSI are either bipolar or metal oxide semiconductor field effect (MOSFET) transistors, diodes or capacitors. The characteristic length scale—at present at about 0.5 microns—will shrink in the future to 350 nm and even to 100 nm. The concentration of dopants, for example arsenic, boron, or phosphorous, in an active region of a semiconducting device ranges typically from $10^{15}/cm^3$ to $10^{20}/cm^3$. It will become necessary to control the variation, or profile, of dopants with a lateral resolution of 10 nm and a vertical resolution of 2–3 nm to accomplish predictability in device behavior and control of the manufacturing process. However, currently known dopant profilers are unable to provide this high precision, at least in all three dimensions.

Known approaches to dopant profiling include junction staining as described by S. T. Ahn and W. A. Tiller in the J. Electrochem. Soc. 135 (1988), p. 2370, dopant density selective etching with Transmission Electron microscopy (TEM) as described in the J. Vac. Sci. Technol. B 10 (1992), p. 491, by H. Cerva, Secondary-Ion Mass Spectroscopy (SIMS), Spreading Resistance (SR), and macroscopic Capacitance-Voltage (C-V) measurement, all described for example in S. M. Sze, "VLSI Technology", McGraw-Hill Book Co., New York, 1983 (in particular chapters 5 and 10). Other methods, currently under development are dopant density selective etching with a Scanning Tunneling Microscope (STM), which is known from L. P. Sadwick et al., J. Vac. Sci. Technol. B 10 (1992), p. 468, planar STM, described by H. E. Hessel et al. in J. Vac. Sci. Technol. B 9 (1991), p. 690, and cross-sectional STM, described by J. M. Halbout and M. B. Johnson in J. Vac. Sci. Technol. B 10 (1992), p. 508. Though being in some aspects useful, these techniques suffer from several drawbacks: they are either destructive or require a careful sample preparation, or have a limited lateral resolution or sensitivity to dopants.

One of the most recent methods to determine the dopant concentration is the Scanning Capacitance Microscope described in the U.S. Pat. No. 5,065,103. It shows features of the scanning probe microscopy and of the conventional C-V technique. But even the Scanning Capacitance Microscope lacks a sufficient lateral resolution as will be required in the future. Further, it employs a lock-in technique to reduce the noise due to stray capacitance thus slowing down the scan process and makes a high throughput by this method improbable.