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SCANNING PROBE MICROSCOPY AND SPECTROSCOPY: FROM BASIC RESEARCH TO INDUSTRIAL APPLICATIONS

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Keywords: semiconductors, semiconductor devices, semiconductor storage devices, UHDS devices, Ultra High Density Storage devices, SPM, Scanning Probe Microscopy, IC, Integrated Circuits, defect analysis, process characterization, process monitoring, creation of nanostructures. STM, Scanning Tunnelling Microscopy, SFM, Scanning Force Microscopes, nanolithography, SCM, Scanning Capacitance Microscopes, NOS heterostructures, Nitride-Oxide-Silican heterostructures, FWHM, Full Width at Half Maximum, ROD, Rotating Disk device, EFM, Electrostatic Force Microscopes, MFM, Magnetic Force Microscopes, SThM, Scanning Thermal Microscopes, SNOM, Scanning Near-field Optical Microscopes, LDD, Lightly-Doped Drain

Abstract: An overview of industrial applications of scanning probe microscopy (SPM) is given. The first part describes possible applications for the fabrication of semiconductor devices by SPM-methods and the use of SPM-based techniques for an ultra high density storage (UHDS) device. The second part shows the ability of SPMs as a characterization tool for integrated circuits (ICs). They can be used in defect analysis, process characterization, and monitoring. And they offer the measurement of each significant value with a spatial dimension of less than 100 nm. So the SPM is useful for a fab today, and irreplaceable for a fab in the future.

Vrstična mikroskopija in spektroskopija s sondo: Od osnovnih raziskav do uporabe v industriji

Ključne besede: polprevodniki, naprave polprevodniške, pomnilniki polprevodniški, UHDS naprave pomnilniške gostote ultravisoke, SPM mikroskopija s sondo vrstično, IC vezja integrirana, analiza hib, karakterizacija procesov, nadzor procesov, ustvarjanje nanostruktur, STM mikroskopija vrstična tunelna, SFM mikroskopi s silo vrstično, nanolitografija, SCM mikroskopi vrstični kapacitivni, NOS heterostrukture nitrid-oksid silicij, FWHM širina polna pri maksimumu polovičnem, ROD naprava z vrtečim se diskom, EFM mikroskopi s silo elektrostatično, MFM mikroskopi s silo magnetno, SThM mikroskopi vrstični terimični, SNOM mikroskopi vrstični optični s poljem bližnjim, LDD ponor dopiran rahlo

Povzetek: V prispevku podajamo pregled uporabe vrstične mikroskopije s sondo (SPM) v industriji.V prvem delu opisujemo možnosti uporabe SPM metod pri izdelavi polprevodniških elementov, kakor tudi uporabo SPM tehnik za izdelavo spominskih elementov z zelo visoko gostoto (UHDS) zapisa informacije.

V drugem delu prikažemo zmožnosti metod SPM kot orodja za vrednotenje integriranih vezij. Lahko jih uporabimo pri analizi napak ter vrednotenju in nadzoru procesov. Metode omogočajo meritve različnih parametrov s prostorsko ločljivostjo, boljšo od 100 nm. Danes je SPM zelo koristna metoda v proizvodnji integriranih vezij, v bodočnosti pa bo postala nenadomestljiva in nujno potrebna.

1. Introduction

Fifteen years after the invention of the scanning tunneling microscope (STM) /1/, scanning probe microscopy (SPM) /2/ is going to be a standard tool for industrial application. Two possible fields are visible today, first the field of fabrication of nanostructures, and second the field of analysis of nanostructures. Both fields are determined due to future development of structures of less than 0.3 μm. Not later than 2005, there must be inventions for the fabrication and analysis of structures with spatial dimensions of less than 100 nm.

SPM offers an interesting combination of high spatial resolution, high sensitivity, and applicability under ambient conditions. Selected examples of applications of SPMs are presented, including fabrication of nanostructures for semiconductor devices and for UHDS devices, as well as SPM-based characterization tools for ICs.

2. Applications of Scanning Probe Microscopy

All different types of SPMs are based on the same principle: a small probe is brought in close proximity to a surface, so that the near-field interaction can be measured. A feedback system keeps the interaction strength constant during the scan.

2.1 Applications of SPM for the creation of nanostructures

By SPM it is possible to create structures with spatial dimensions of less than 100 nm, due to an increase of the interaction between probe and sample. This ability can be used for the fabrication of semiconductor devices, as well as for basic technology for a future UHDS device.

2.1.1 Semiconductor devices

Atomic manipulation has been shown with a STM /3/, but this required a great technical effort (UHV, 4°K). Nanolithography has been demonstrated with a scanning force microscope (SFM) /4/ for integrated fabrication of semiconductor devices /5/ and of quantum electronic devices /6/. This manipulation has been done at ambient conditions.

A conducting SFM tip was used to write nanometer scale oxide patterns on a Si(100) surface and on amorphous silicon. These patterns can be used as masks for selective etching of the silicon, and enable the fabrication of a 0.1 μm metal-oxide semiconductor field-effect transistor (MOSFET) /5/. Based on anodic oxidation of thin Al films with an SFM, the fabrication of atomic point contacts has been shown /7/.

Furthermore, the SFM can be used to generate patterns on a photoresist. Wendel et al. /6/ generated hole arrays with a periodicity down to 35 nm and a hole diameter of only a few nanometer. Mechanical surface modification techniques have been applied to hard materials too, like superconducting ceramic, using a SFM with a diamond probe tip /8/.

All these nanolithography techniques work very well, but relatively slow. A commercial SFM works with scan velocities on the order of a few μm/s. To overcome this great disadvantage, Minne et al. /9/ have developed a cantilever with integrated piezoelectric actuator. With this cantilever, they have reached tip velocities in feedback operation of up to 1 cm/s, that leads to more than 20 frames (50 μm x 50 μm) per minute. Furthermore, they developed an array of 2 x 1 individually controlled cantilevers. Binnig et al./10/ presented the development of an array of 5 x 5 cantilevers. Future development will give us arrays of even 100 x 100 cantilevers, so we will be able to scan and manipulate a field of more than 2 cm x 2 cm per minute. From then on, we can use SPM technology for industrial fabrication of semiconductor devices of the 0.1 μm generation.

2.1.2 Ultra High Density Storage Devices

Another interesting field of application for SPM-based technologies are UHDS devices. Up to date hard disks reach data densities of less than 2 Gbits/in^2, and the border line for conventional storage technology is on the order of several tens of Gbits/in^2 because of limitations regarding superparamagnetics in magnetic recording and optical diffraction in optical recording. But nevertheless, there is an increasing demand for higher data capacities. So there must be research in unconventional developments for new storage devices. With a STM, one can manipulate single atoms and reach a data density of 10^6 Gbits/in^2. The disadvantages are the great technical effort and the slow scan speed and data transfer rate respectively. To use other types of SPMs seems to be a better approach.

Kino et al. /11/ developed a solid immersion lens scanning near-field optical microscope (SIL-SNOM). With this technique Terris et al. /12/ achieved a data density of 2.5 Gbits/in^2 and a data rate of 3.3 Mbits/s.

Recently, Martin et al. /13/ presented a scanning interferometric apertureless microscope (SIAM), where a resolution of 50 nm was achieved with visible light. This corresponds to a potential density of 256 Gbits/in^2. A theoretical calculation gives a possible data rate in the tens of MHz range. The scanned sample was an SiO_2-Si disk with smallest pits of 50 nm x 50 nm across, and 25 nm deep, fabricated by electron (e) -beam lithography and reactive ion etching.

Another read-only-memory (ROM) device with a data density of more than 50 Gbits/in^2 has been demon-

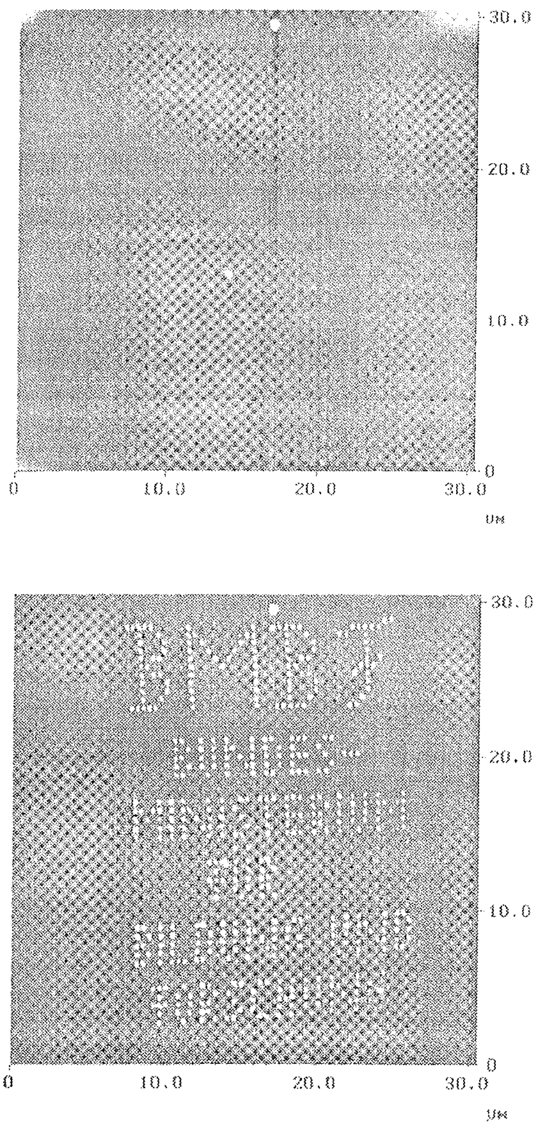

Fig. 1: *Topography and capacitance image of a NOS heterostructure with stored charge dots.*

strated by Terris et al. /14/. They used a polycarbonate disk with smallest pits of 100 nm, and an SFM for read out. The disk was manufactured from an e-beam generated master pattern. This technology enables mass production of samples with pits of less than 50 nm /15/. The used SFM works in contact mode with special high-frequency piezoresistive cantilevers with resonance frequencies of up to 10 MHz. Furthermore, Terris et al. have developed a SFM-based system with a rotating sample. A new autotracking system could maintain the tip on a particular data track. So they get a data density of 65 Gbits/in^2 and a data rate of more than 1 Gbits/s.

A possible random access memory (RAM) UHDS device is based on a scanning capacitance microscope (SCM) and on charge storages in a nitride-oxide-silicon (NOS) heterostructure (Fig. 1). A voltage pulse of typically 40 V and 10 μs allows the charging of the nitride-oxide interface, and a voltage pulse of the opposite direction can discharge this interface.

The smallest structure written in our laboratory had a full width at half maximum (FWHM) of 160 nm. The maximum data density reached is more than 30 times higher than in today´s commercial storage memories. The theoretical data density limit determined by the overlap of the depletion areas is more than a hundred times higher. To reach high data rates, a SCM-based prototype (rotating disk (ROD) -device) has been developed that rotates the sample (Fig. 2).

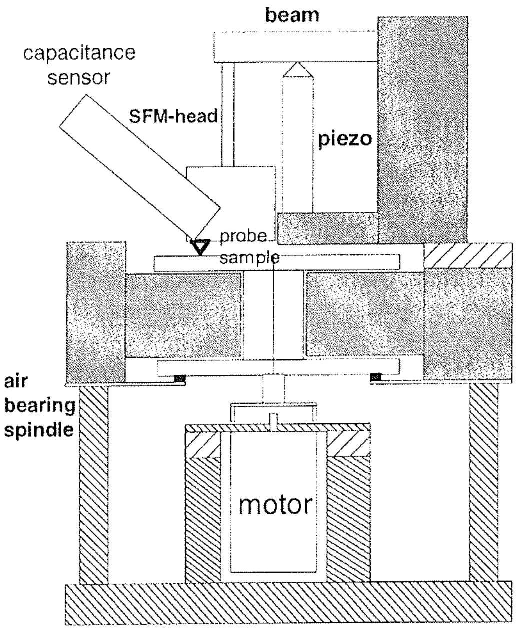

Fig. 2: Schematic of the ROD-device.

The SCM head can be moved by a high-power piezoelectric element in z-direction, so that the cantilever is pressing on the surface with a force as small as possible. First tests gave us data rates of more than 100 kHz, with a signal to noise ratio of 60 dB. The great problem of this storage technology is the contact between the metallic tip of the cantilever and the very hard silicon-nitride surface. At relative velocities of some meter per second, the tip gets rubbed off and the resolution of the system and its data density decrease as a function of time. This wear problem can be expected to be diminished by development of new coating technologies or non-contact measurements.

All these approaches show the possibility to use SPM-based techniques for a future UHDS device.

To summarize: SPM offers a great potential for the creation of nanostructures, and can be used for the fabrication of 0.1 μm semiconductor devices and for UHDS devices.

2.2 Application of SPM for the analysis of nanostructures

SPMs are predestined for the characterization of ICs, due to their two-dimensional (2-d) imaging capabilities, high spatial resolution, and nondestructive nature. There is a great need for nanometer-scale measurements in the semiconductor industry. The family of SPMs offers the detection of each significant value (Fig. 3).

Interaction	Microscope	Abbreviate
Electric field	Electrostatic force microscope	EFM
Magnetic field	Magnetic force microscope	MFM
Heat	Scanning thermal microscope	SThM
Light	Scanning near-field optical microscope	SNOM
Capacitance (doping profile)	Scanning capacitance microscope	SCM

Fig. 3: Overview of SPM types for the characterization of ICs.

A SFM can be used for cross section inspection and metrology /16/. The measurement error introduced by the finite size of the cantilever tip can be calculated due to computer models. Therefore, the SFM image gives us the exact values compared with a scanning electron microscope (SEM) measurement, but without the effort of specially prepared samples.

An electrostatic force microscope (EFM) enables the measurement of an electric field and therefore a voltage on an IC, with spatial dimension of less than 100 nm. Furthermore, special techniques (heterodyne mixing) enable the measurement of voltages with frequencies of some tens of GHz /17/.

The magnetic stray field of a conductor track can be measured by a magnetic force microscope (MFM). A calculation gives us the current of the conductor. In addition, the MFM has been used for the measurement of the stray field of write-read heads of hard disks.

The scanning thermal microscope (SThM) allows us the detection of hot spots on an IC with 100 nm resolution /18/.

A very interesting analytical device is the scanning capacitance microscope /19/. The SCM offers the detection of 2-d doping profiles with lateral resolution of less than 100 nm and dopant concentrations of 10^{15} to 10^{20} cm^{-3}. The „National Technology Roadmap for Semiconductors" describes this measurement as decisive technology for the next generation of ICs. The SCM permits determination of the effective channel length and the lightly-doped drain (LDD). Exact data are very important for the optimization and calibration of technology computer aided design (TCAD) systems, and new designs of MOS-FETs and Bipolar-transistors require an exact knowledge of the 2-d doping profiles (Fig. 4).

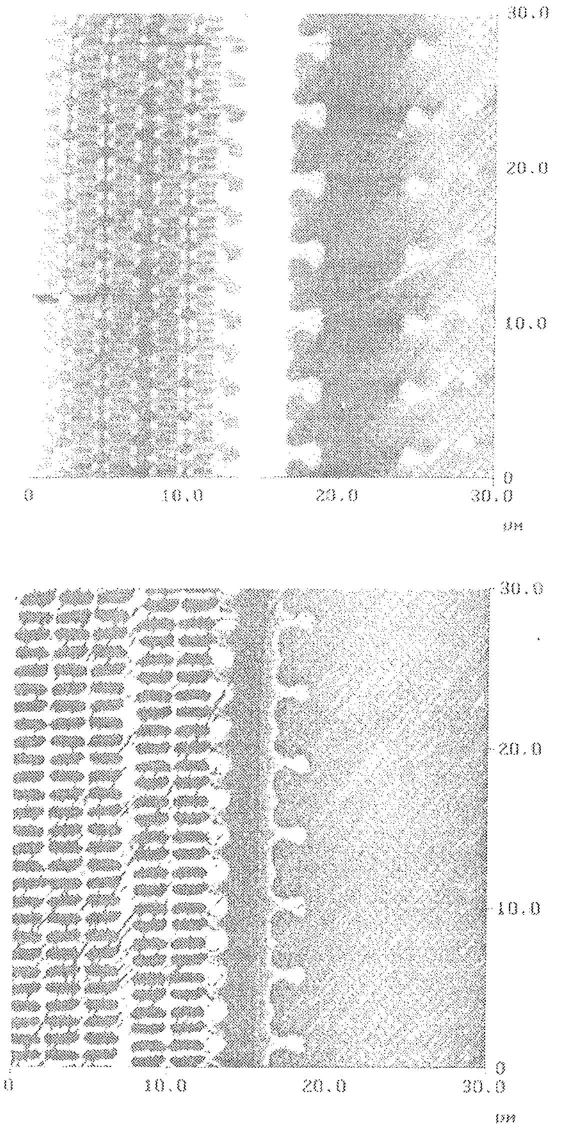

Fig. 4: Topography (upper) and capacitance image of a DRAM.

For spatially resolved SCM measurements complete C(V)-V-curves were not taken, but the capacitance was measured at a constant bias voltage. The result is a capacitance image of the sample. The problem of inversion - determination of the dopant concentration from measured capacitance images - is not solved yet, since too many factors are unknown.

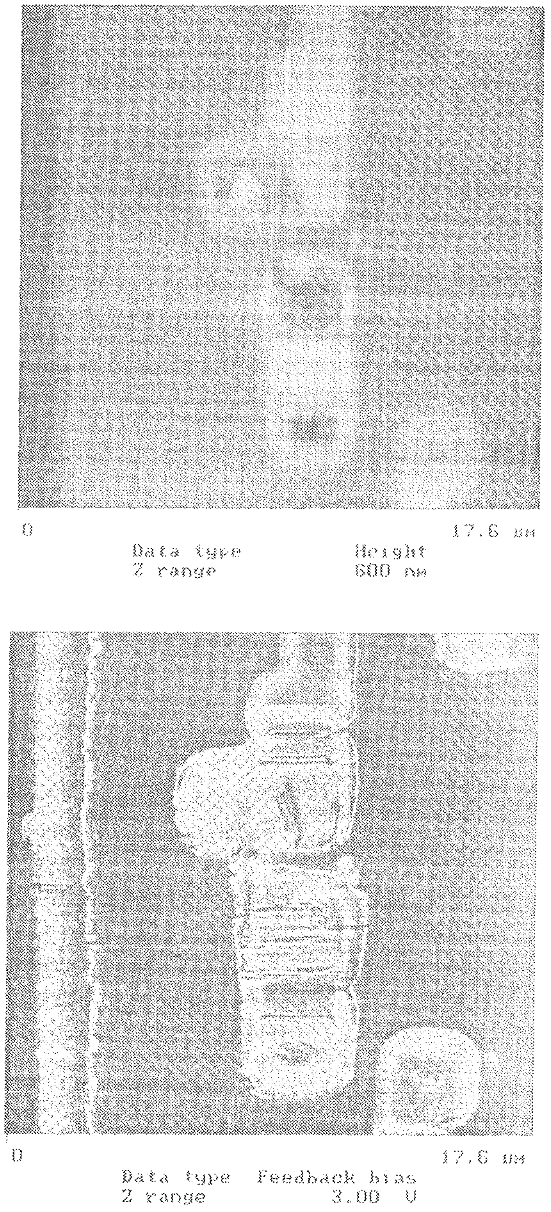

Fig. 5: Topography (upper) and capacitance image of an electrostatic discharge.

These unknown facts are, e. g., the influence of the shape of the probe, the thickness, and the dielectric constant of the oxide. Nevertheless, capacitance images of manufacturing IC-structures have a great potential for use in defect analysis, process characterization and monitoring. Fig. 5 shows the topography and the capacitance image of a sample with an electrostatic discharge. This is the main reason for ICs being destroyed, and often invisible in SEM. On the other hand, the SCM gives us an exact image of the topography and the expected flow of dopant atoms. So SCM is already in use in industry and research institutions for process development and failure analysis.

3. Conclusion

SPM offers a great potential for the creation and analysis of structures with spatial dimensions of less than 100 nm. SPM can be used for fabrication of future masks and the fabrication of semiconductor devices, as well as basic technology for UHDS devices. Furthermore, SPM can be used as a characterization tool for the semiconductor industry.

To summarize: SPM is going from lab to fab.

4. Acknowledgments

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