Voltage Contrast in Microelectronic Engineering

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Date: March 2013
Original publication September 2012

The interaction of a charged particle beam with structures of different electric conductivity in a microelectronic circuit locally changes the electric potential at its surface. In a scanning electron microscope (SEM), this effect leads to a distinct voltage contrast superimposed on the image. It is very useful for failure analysis and device debugging in microelectronic research and development.

Introduction

Bulk insulating specimens, or insulated layers on a conductive substrate with a thickness larger than the electron range, charge up when irradiated by the electron beam in the SEM. If the combined drain of backscattered and secondary electrons exceeds the supply of primary beam electrons, a positive net charge results that generates a positive electric surface potential. The trajectories of primary, secondary and backscattered electrons are influenced by this potential. Part of the secondary electrons will be prevented from reaching the detector. Thus, insulated structures will appear darker in the secondary electron image than grounded structures that do not charge (Fig. 1). This phenomenon is called passive voltage contrast. Electrical opens, for instance in contact chains, can be easily found with this method.

In integrated circuits, electric surface potentials can also be actively controlled by applying voltages to selected interconnects. The connected structures will then be visible with different contrast in the secondary electron image. Similar to passive voltage contrast, positive regions appear dark, while negative regions appear bright (Fig. 2). This active voltage contrast is used to detect dielectric leakage or metallisation shorts. Moreover, active elements in the device under test can be dynamically driven, enabling waveform and timing measurements.

Active voltage contrast on microelectronic devices requires precise probing using micromanipulators. Interconnects can be contacted using a single microelectrode tip to apply a voltage against the grounded substrate, and closed electrical circuits can be constructed by contacting with two or more tips simultaneously. A tip positioning accuracy in the nano-metre range, low drift, low backlash, and insusceptibility to vibrations of the micro-probing setup are indispensable for successful use of this method on modern nanoscale interconnects.

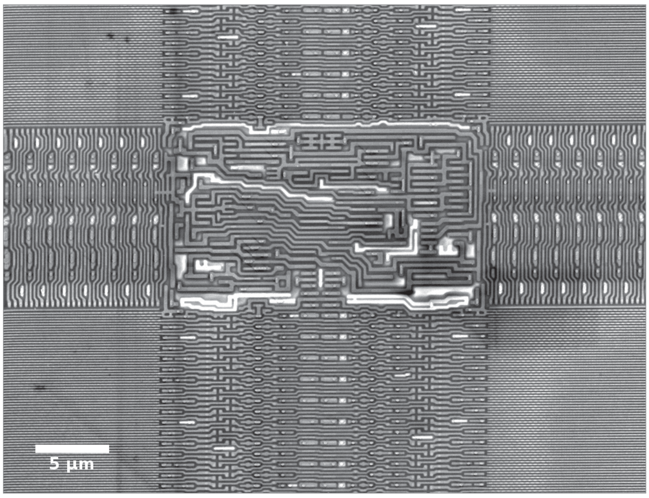

Fig. 1. *Passive voltage contrast on an integrated circuit.*

Solution

Voltage contrast on current integrated circuits requires an SEM with high secondary electron detection efficiency and nanometre lateral resolution. In addition to that, micromanipulators with nanometre accuracy for controlled electrical contacting are needed to actively modify surface potentials on circuit structures.

The final lens of the ZEISS GEMINI FE-SEM column is electrostatic and does not impose a magnetic field on the sample. The trajectories of the emitted electrons are preserved. The highly efficient in-lens secondary electron detector detects almost purely secondary electrons based on their trajectories in the column. Both features contribute to a strong and clean voltage contrast on microelectronic structures.

The excellent low-voltage performance of the GEMINI column allows the use of low acceleration voltages for voltage contrast. Thus, image distortions and contrast artefacts due to excessive local sample charging are minimized. Passive and active voltage contrast can be precisely fine-tuned, while maintaining high image resolution.

Micromanipulator devices that fulfil the requirements for active voltage contrast experiments on state-of-the-art microelectronic structures are available from various vendors and can be easily integrated with ZEISS instruments.

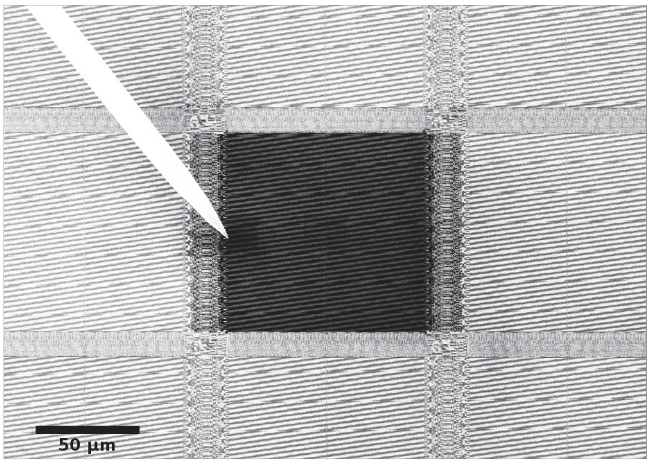

Fig. 2. *Highlighting an interconnected circuit area by biasing with a micro-electrode tip.*

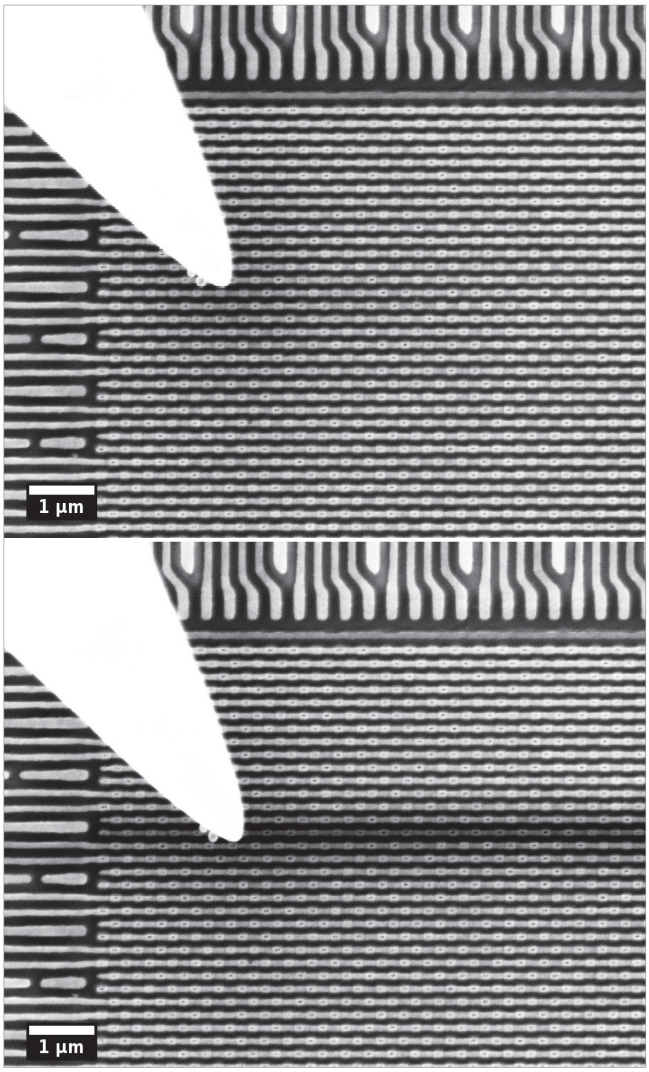

Fig 3. *Selective biasing of a single, 100 nm wide interconnect line.*
Top: Before tip contact. Bottom: Contacting the line.

Application Examples

All images shown here were recorded on a memory circuit sample, using the GEMINI SEM column at 2 kV acceleration voltage and 5 mm working distance, and the in-lens secondary electron detector.

Fig. 1 shows an example of passive voltage contrast. The in-lens secondary electron detector signal produces strong voltage contrast without interfering topography contrast, and without superposed material contrast from back-scattered electrons.

A typical active voltage contrast image can be seen in Fig. 2. For the examples shown here, Kleindiek Nanotechnik MM3A piezo micromanipulators were used. For the electrical biasing, etched tungsten wire tips were attached to the micromanipulators and connected to a 6 V battery pack. Selective highlighting of an individual 100 nm wide interconnect line is presented in Fig. 3. Contacting individual interconnects in a more complex structure is shown in Fig. 4.

Fig. 5 demonstrates active voltage contrast using two tips to apply a voltage to the ends of contact chains. The gradual voltage drop along the chains (due to its electrical resistance) becomes visible as a gradual decrease of the contrast along the chain structures. The structural detail of the sample remains fully resolved.

The tracing of long interconnect lines to locate opens or shorts is greatly facilitated by the large beam shift option of the GEMINI column. Its approximately +/-150 µm beam deflection range permits the movement of the scan field along interconnects at high magnification over a very long distance (Fig. 6).

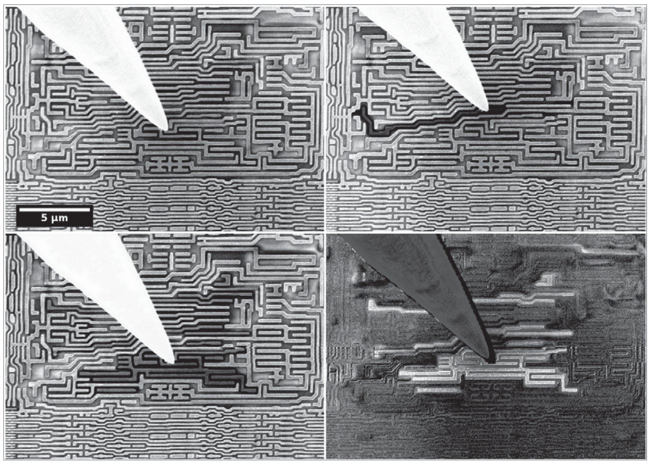

Fig. 4. *Selective biasing of adjacent interconnects. Top left: Before tip contact. Top right and bottom left: contacting two adjacent lines. Bottom right: Difference image between the two images on the left.*

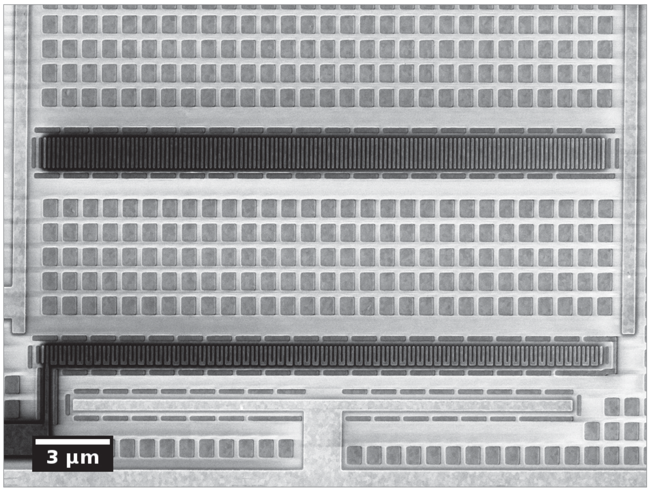

Fig. 5. *Closed circuit biasing of contact chain structures using two tips (Tips not show in the image). The voltage drop along the chain structures becomes visible as a gradual decrease of voltage contrast.*

Conclusion

As shown in these examples, the ZEISS GEMINI FE-SEM column provides excellent voltage contrast on microelectronic samples. Strong passive voltage contrast is easily achieved. Active voltage contrast experiments that require precise contacting of interconnect structures can be carried out even with a simple and cost effective micro-probing setup. Another benefit for failure localization is the large beam shift option. In many cases, it can avoid time consuming moving of the sample and repeated positioning of the tips.

An additional means for failure investigation in micro-electronic circuits is the focused ion beam. Structures can be made floating by interrupting their grounding with the ion beam (not shown here). They can be grounded by ion beam cutting followed by ion beam induced metal deposition. In an instrument that combines SEM and focused ion beam, such as ZEISS AURIGA, these operations can be done under simultaneous control of the resulting voltage contrast changes with the GEMINI column.

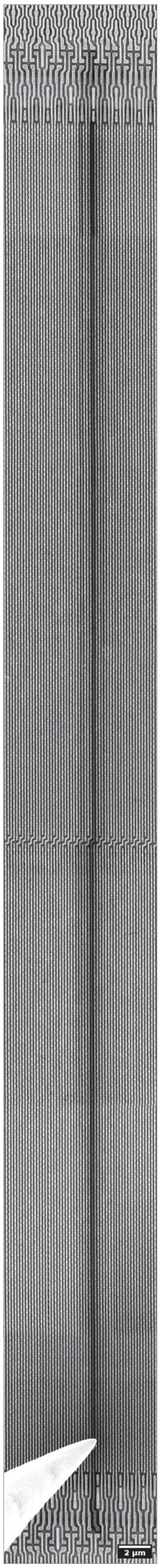

Fig. 6. *Montage of seven images recorded by moving the scan along a highlighted interconnect line over more than 90 µm using the large beam shift option of the GEMINI column.*