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ELECTRON DETECTORS FOR ELECTRON-BEAM TESTING
OF ULTRA LARGE SCALE INTEGRATED CIRCUITS

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Abstract

The increasing density of components in integrated circuits imposes severe constraints on conventional electron beam testers. The use of electron detectors consisting of combined electrostatic and magnetic fields has demonstrated improved performance over conventional electrostatic detectors. Such detectors also ease many of the practical difficulties associated with electron beam testing of Ultra Large Scale Integration (ULSI) circuits. A detector using a single pole magnetic lens will be described and compared to detectors which use only electrostatic fields. The single pole lens detector has demonstrated superior performance to the electrostatic detector in terms of local field error and imaging resolution, allowing accurate measurements to be made on sub-micron structures.

Introduction

Electron beam testing is finding increasing acceptance within the semiconductor industry as a device analysis tool. The principle on which the technique depends has been known for over a quarter of a century but it is only in recent years that the need has been sufficient to justify the investment. The reasons for using electron beam measurement of waveforms within operating integrated circuits have been documented many times (e.g., Wolfgang, 1983; Hohn, 1985). Indeed, it has been demonstrated that under favorable conditions it is possible to measure waveforms with time resolution of picoseconds (Hosokawa et al, 1978) or voltage resolution of millivolts (Menzel and Kubalek, 1979). When measurements are attempted on integrated circuits, however, the situation changes considerably. In particular, a number of additional factors are introduced which influence the attainable voltage resolution.

The mechanism of voltage measurement using an electron beam has been described in detail elsewhere (e.g., Feuerbaum, 1982). An electron beam strikes the sample at the point where the voltage is to be measured and secondary electrons are emitted. The energy distribution of the electrons is considered to remain constant with respect to the voltage measurement point. If a potential barrier is placed above the sample and set at V volts more negative than the sample then only electrons with sufficient energy will be able to surmount the barrier and be collected. If the measurement point were to change voltage by $+v$ then only those electrons with sufficient energy to surmount a potential barrier of $(V+v)$ volts will be collected and, therefore, the collection current will reduce. It may be seen that if the potential

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barrier is adjusted such the the collected current is constant (i.e., that the potential between the barrier electrode and the sample is held constant) then changes in the sample potential will be followed by equal changes in the barrier potential. This forms the basis of electron beam waveform measurement.

The major source of error in this measurement scheme is caused by changes in the collected electron current which do not correspond to changes in the sample potential. The most fundamental cause of this is the statistical variation in the number of electrons collected, or shot noise (See for example, Sackett and Spicer, 1986). This limits the attainable resolution in terms of the beam current, measurement time, required bandwidth and other factors. However, if sufficient time is spent making a measurement the effect of this source of noise can be minimized. In addition, the collected current may vary due to fluctuations in the measured secondary electron energy distribution, either because of variations in the secondary emission from the surface of the material or non-linearities in the electron detector.

The secondary emission characteristics of a material will change with time as the sample is irradiated. The most common cause is very thin layers of material being deposited onto the sample surface. This is commonly polymerized oil from the residual gasses in the vacuum system. Since secondary emission occurs from only the first few atomic layers of most materials this can affect their energy distribution.

The detector itself can be a source of error. If the electron collection depends on any other parameters such as the electron energy, filter bias potential or extraction voltage then systematic errors will be introduced into the voltage measurements. Such errors can be reduced by extensive computer simulation of the detector under a range of operating conditions.

Additional sources of error can be caused by the electron detection method. A conventional planar secondary electron detector is shown in schematic form in fig 1. This kind of detector is not a true electron energy analyzer for electrons which travel at some angle to the vertical since an electron will still have some energy (in the form of velocity in the lateral direction) even if it has instantaneously stopped in the vertical direction. Therefore, the greater the angle of emission of the

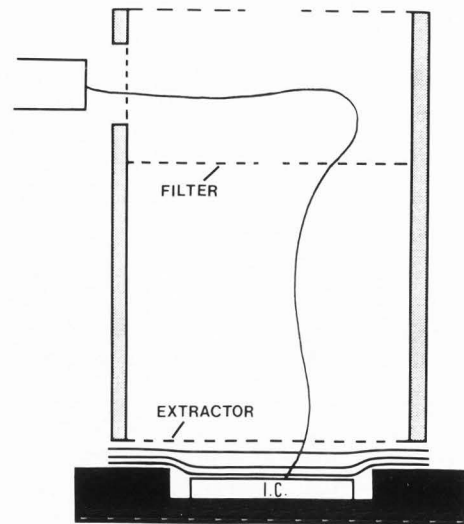


Fig. 1. Schematic of a planar electrostatic electron spectrometer. Electron energies are only accurately measured if the electron is emitted vertically.

electron, the more initial energy will be required to pass a barrier electrode at a given potential.

Secondary electrons are emitted in all directions but as long as the relative proportions of electrons emitted at different angles is constant then planar electron detectors operate satisfactorily. However when an integrated circuit is operating there

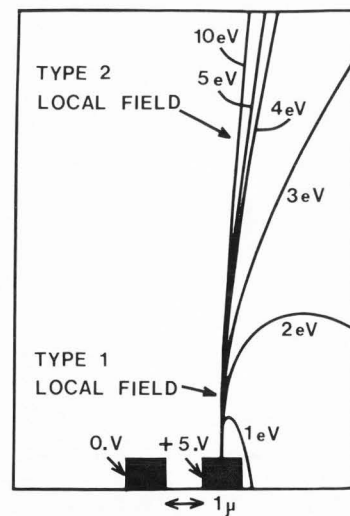


Fig. 2. Trajectory plot of electrons emitted vertically. The local electric field due to the voltages on the tracks alter the angle of the electrons and may return low energy electrons to the surface of the chip.

are electric fields close to the surface of the device which can alter the trajectories of the low energy secondary electrons (fig 2). This has two important effects; if the potential of the point to be measured is positive with respect to the surrounding region then there will be a local retarding field which will return low energy secondary electrons back to the sample. If an electron escapes the surface then irrespective of the direction of the local electric field, the electron will be to some extent focussed by the field. This systematic variation in the mean emission angle of the electrons causes a similar systematic error in the collected electron current (and hence in the apparent surface voltage). This effect is generally known as the "Local field effect" and can cause unacceptably large errors on small geometry devices (Wager and Wolf, 1985).

Numerous attempts have been made to reduce this error. It is possible to minimize the number of electrons which are returned to the surface of the sample by superimposing an electric field which tends to draw the electrons towards the detector. Unfortunately, the field strengths required determine that an electrode at a potential of hundreds or even thousands of volts must be placed within a few millimetres of the sample. Such arrangements have many practical disadvantages and can lead to leakage currents in circuits (by partially inverting lightly doped regions) and charging of insulating regions. In addition, the method does little to reduce the change in the lateral component of velocity of the electrons.

Some workers (e.g., Goto et al, 1981; Nakamae et al, 1985) have used detectors with a hemispherical potential barrier. If the electrons are assumed to have been emitted from a point at the centre of the hemisphere then each will be influenced by a retarding field in the opposite direction to the electrons' velocity. In principle, this kind of detector is a total energy spectrometer because it will measure the same result irrespective of the angle of emission of the electrons. In practice it has been found difficult to design a detector where the potential lines are accurately hemispherical, so limiting the improvements in performance.

In 1984 Menzel introduced a spectrometer which consisted of a conventional planar electrostatic detector located within the final magnetic lens of a SEM. This arrangement demonstrated significant

improvements over conventional electrostatic electron detectors. The local field effect was shown to be reduced and the sample could be placed close to the final lens of the SEM for high resolution imaging.

The Single Pole Spectrometer

Electron beam testing is used principally to evaluate integrated circuits in the design development phase. Therefore, by definition, the technique will be used on circuits with state-of-the-art speed and packing density. Conventional electron beam test equipment will give errors of approximately 33% on structures with 1 micron lines and spaces (Garth et al., 1986) and even the best equipment commercially available has been shown to give errors of the order of 10% under similar circumstances.

A detector has been developed which systematically minimizes the local field error. Prototype systems demonstrated worst-case local field error of approximately 2% on structures with 0.5 micron lines and spaces, with 5V signals applied. The principle and local field performance have been described in detail elsewhere (Garth et al, 1986) as illustrated by the schematic in Figure 3. The sample is placed in a magnetic field such that the field strength decreases in a controlled way above the sample. When a secondary electron is emitted, it

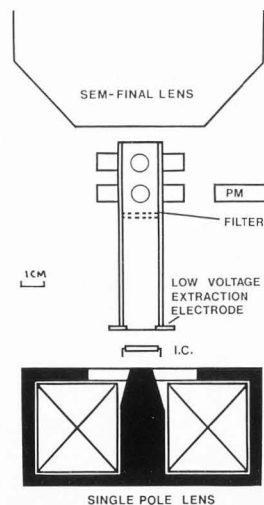


Fig. 3. Schematic of the single pole detector. The electrons are guided by the magnetic field and unspirals as they pass into the low field region. The electrostatic analyzer now accurately measures the total energy of the electrons irrespective of their emission angle.

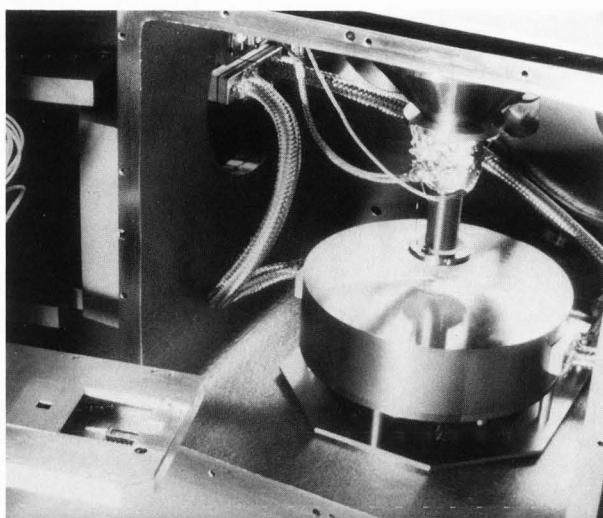


Fig. 4. The arrangement of the detector and the single pole lens in a conventional scanning electron microscope.

spiral in the magnetic field and moves upwards. As it does so, it encounters a region of lower field and the radius of rotation increases. The field is designed to be adiabatic, so that the angular momentum of the electron is conserved. The increase in the radius of rotation causes the electrons' circumferential velocity to reduce (to conserve angular momentum) and a subsequent increase in the axial velocity (to conserve total energy). In this way the electron "unspirals" as it passes through the detector, arriving at the region of low magnetic field travelling almost parallel to the axis. A planar electrostatic energy analyzer will now measure a good approximation to the total energy of the electrons, independent of the angle of emission or any angular perturbations which may occur close to the sample surface. In this way, the effect of local electric fields is minimized.

Such a detector cannot easily be placed into a conventional scanning electron microscope. However, with certain other developments, further advantages of this detector system over conventional electron detectors can be realized. The overall arrangement is shown in fig 4. The magnetic field is provided by a single pole magnetic lens placed below the sample. Above the sample is the electrostatic detector body which mounts on the final lens of the SEM.

In electrostatic energy analyzers, it is conventional to collect the secondary electrons by applying an electrostatic field perpendicular to the electron axis. Thus the secondary electrons are drawn into a collector at the side of the detector. This arrangement has been shown to give non uniform collection depending on the energy of the electron to be collected (Menzel and Brunner, 1983). This may be corrected by varying the mean potential of the entire collection system in parallel with the filter electrode but this severely limits the bandwidth of signals which can be applied to the filter electrode. In addition, the unbalanced lateral field causes deflection, energy spread and astigmatism in the primary beam. This can lead to inadequate imaging performance from the detector.

The secondary electrons of interest have energies of 0-20 eV. In addition, the sample voltage measurement may lie in the region $\pm 15V$. In this example, therefore, the difference in energy between the most and least energetic electron to be collected is 50eV. If the primary electron beam energy is 1keV, a conventional collection system will have a severe influence on the beam. These difficulties may be minimized with the use of a collection system as shown in fig 5. The system

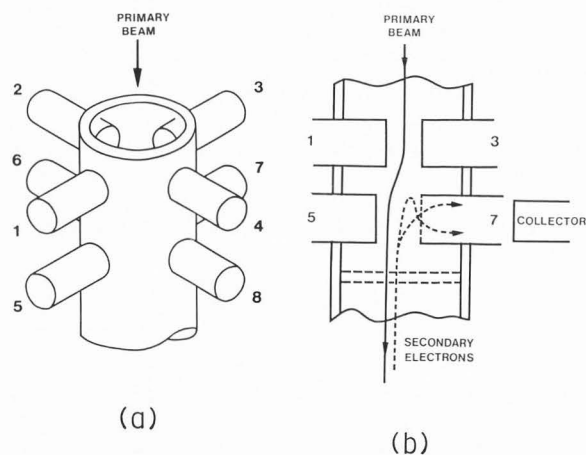


Fig. 5. a) Overall view of the electrostatic double-stigmator structure. b) Cross section of the double stigmator electron collector. Secondary electrons are collected in electrode 7 and any errors which are caused on the primary beam are corrected by the other electrodes.

consists of two electrostatic stigmators placed above each other. Electrode 7 is more positive than electrode 5 and electrode 3 is more negative than electrode 1. The primary beam enters from the top and is deflected towards electrode 1 by the top stigmator and towards electrode 7 by the lower stigmator. The potentials are so arranged that the primary beam exits the collector in the direction of the point where the axis meets the sample surface. In this way, energy spread in the primary beam and net deflection of the beam position are eliminated. The other two electrodes of each stigmator are set to minimize any residual astigmatism.

The mean potential of the lower set of electrodes is set more positive than the most positive sample potential. Therefore no secondary electrons are reflected by the lower electrodes. The mean potential of the upper electrodes is set more negative than the most negative sample potential minus the maximum energy of secondary electrons to be collected. Therefore, no secondary electron of interest will pass the upper electrodes. The collection electrode (7) is hollow and has on its face a grid. Secondary electrons pass up from the filter grid and are deflected through the grid on electrode 7, to be collected by the standard electron microscope photomultiplier.

Therefore, the detector collects all the secondary electrons of interest while having a minimal effect on the primary electron beam. In addition, backscattered electrons will be focussed by the single pole lens through the stigmator electrodes. Any tertiary electrons which are subsequently generated will be prevented from entering the collection system by the negative potential of the upper set of electrodes.

The high voltage extraction electrode found on conventional electron spectrometers is not suited to the single pole detector. It may be eliminated and replaced by a low voltage electrode (50V) if the closed loop operating point is set at approximately the power supply voltage. Under these conditions, any electrons whose energy is low enough that they may be returned to the surface of the sample by the local electric fields are not included in the waveform measurement. This reduces the total number of secondary electrons which may be collected but for 5V logic circuits, this has not been found to be a problem.

In addition to the elimination of the difficulties described earlier, there are significant advantages to removing the high voltage extraction electrode. When a primary electron beam strikes an insulating layer, either adjacent to a track or when measurements are being made under a passivation layer, some charging will generally occur. If the primary beam voltage is chosen so that the insulator has a secondary emission coefficient greater than unity then the surface charges positively. As this happens, local fields are set up and low energy secondary electrons are attracted back to the sample surface. This causes the effective secondary emission coefficient to tend towards unity and a stable situation occurs at a surface potential of about +2V. If there is a strong extraction field then the local fields will not return the electrons and the surface will charge severely introducing instability and error into the waveform measurement. If the single pole detector is used without an extraction field then positive surface charging effects are minimized.

A characteristic of all previously reported electron spectrometers is the desire to minimize the distance from the final lens to the sample. In addition, the distance between the extraction electrode and the sample is minimized so that the maximum extraction field possible is obtained for a given extraction voltage. This makes the inclusion of a probe card stage to make measurements on a wafer difficult. In addition, the proximity of the voltages on the probe pins can cause local field effects. The elimination of the extraction electrode and the introduction of an additional magnetic lens below the sample eases these constraints. The effective working distance due to the single pole lens is very short but there is almost no constraint on the distance between the final lens of the SEM and the sample, nor the detector and the sample. This makes the inclusion of a probe card stage considerably easier. In addition, the properties of the single pole detector minimize the error due to angular variation of the secondary electrons from voltages on the probe card pins.

Generally in electron optical systems there is a trade-off between the field of view and the resolution attainable. In scanning electron microscopes these values are set by varying the working distance. However, the dimensional constraints of the electron beam test systems often make it

difficult to vary the working distance. The single pole detector is more flexible in this regard. The primary electron beam may be focussed by either the final lens of the SEM or the single pole lens or partly by both. The former case gives a very wide field of view and the latter gives optimum resolution. This is approximately equivalent to electrically altering the working distance and is especially useful for quickly locating and then making a waveform measurement on a small detail within a large circuit. An example of the image quality available is shown in fig. 6. The imaging resolution is more than adequate to measure waveforms on sub-micron tracks.

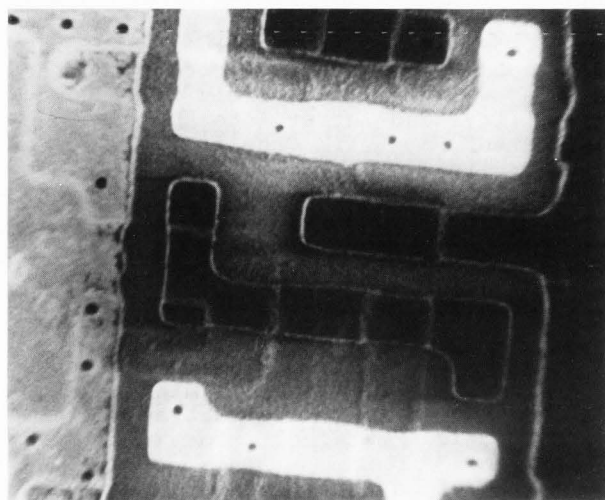


Fig. 6. Voltage contrast image of a 1 Mega-bit Dynamic random Access Memory demonstrating the imaging resolution attainable. Photo width = 30 μ m.

Conclusions

Electron beam testers need to be able to make accurate waveform measurements on state of the art integrated circuits if they are to be used for design development. An electron spectrometer has been described which is capable of waveform measurements of better than 2% accuracy on devices with sub-micron lines and spaces. The arrangement also gives significant practical advantages by eliminating the high voltage extraction electrode above the sample. This leads to greater imaging flexibility and the simpler implementation of waveform measurements on wafer using a probe card.

References

- Feuerbaum HP (1982) Electron Beam Testing: Methods and Applications, Scanning 5, 14-24.
- Garth SCJ, Nixon WC, Spicer DF (1986) Magnetic field extraction of secondary electrons for accurate integrated circuit voltage measurement, J. Vac. Sci. Technol. B, Jan/Feb 1986 217-220.
- Goto Y, Ito A, Furukawa Y, Inagaki T (1981) Hemispherical Retarding Type Analyser for IC Testing by Electron Beam, J. Vac. Sci. Technol. 19 (4), pp 1030-1032.
- Hohn FJ (1985) Background and Applications of Electron Beam Test Techniques, Microcircuit Engineering 1985, (North Holland Press). pp181-182.
- Hosokawa T, Fujioka H, Ura K (1978) Generation and Measurement of Sub-picosecond Electron Beam Pulses, Rev. Sci. Instr. 49, 624-628.
- Menzel E, Kubalek E (1979) Electron Beam Test System for VLSI Circuit Inspection, Scanning Electron Microsc. 1979; I:297-303.
- Menzel E, Brunner M (1983) Characterization and Performance Improvement of Secondary Electron Analyzers, J. Vac. Sci. Technol. B 1 (4), Oct-Dec 1983, 1348-1351
- Nakamae K, Fujioka H, Ura K (1985) A New Hemispherical Retarding Field Analyser for Quantitative Voltage Measurements in the SEM, J. Phys. E: Sci. Instrum., 18, 437-443.
- Sackett J, Spicer DF (1986) Shot Noise Limits to Measurement Accuracy and Bandwidth in E-Beam Testing, J. Vac. Sci. Technol. B, Jan/Feb 1986 213-216.
- Wager WE, Wolf ED (1985) The Effects of Local Electric Fields and Specimen geometry on Voltage Contrast in the Scanning Electron Microscope, J. Vac. Sci. Technol. B, Jan/Feb 1986 209-212.
- Wolfgang, E (1983) Electron Beam Testing: Problems in Practice, Scanning 5, 71-83.

Discussion with reviewers

M. Brunner: What are the practical experiences concerning signal to noise ratio, voltage resolution and measurement times? How do these compare with the Feuerbaum detector?

Authors: The single pole lens allows higher beam current densities at the sample and so reduces the measurement time (the degree depends on how the machine is set up). Otherwise the issues such as contamination, statistical shot noise etc. are identical to the Feuerbaum detector.

M. Brunner: Has the error on conventional spectrometers been observed with the same suppression of low energy secondary electrons as in your system?

K.D. Herrmann: To what extent does the rejection of all low energy secondary electrons account for the reduction of the local field error?

Authors: Local field error measurements have been made at a number of filter bias offsets with only marginal variation in the results. The proportion of the error due to angular variation and to electrons being returned to the surface is sample dependent.

J. Reimer: You refer to a local field error of 2% on structures with 0.5 micron lines and spaces and a 5V signal. Do you actually refer to a voltage measurement error of 2%, attributable to the local field? If so, what was the total voltage measurement error at a 5V signal?

What is the linearity of your measurement system at the absence of local fields, based on a measurement sequence, using a large area conductor?

Authors: The results indicate the error due to local field effects alone. The absolute accuracy is comparable to other electrostatic detectors.

M. Brunner: What is the detection efficiency of the system taking the suppression of low energy secondary electrons into account?

Authors: This has not been measured but the efficiency of the detector appears to be high (due to the confinement of the electrons by the magnetic field). This is then reduced by about a factor of 2 if the filter bias is set at -5V.

K.D. Herrmann: Why can the single pole detector not be used with high extraction fields?

H. Fujioka: Did you have to alter the single pole lens to satisfy the adiabaticity condition?

Authors: The adiabaticity is defined as the proportional change in the magnetic field strength during one electron rotation. Therefore, the field must be

shaped to keep this to a low value and this is difficult if the electrons have been accelerated to a high velocity.

H. Fujioka: Would you please show some typical experimental results.

J. Reimer: Would you please include an example of a typical high-accuracy waveform to show how your waveform is constructed graphically?

Were your measurements on 0.5 micron lines with 0.5 micron spaces made on a test structure or on a functional integrated circuit? Please describe the device on which measurements were made in more detail and provide some results.

Authors: Please refer to reference Garth et al, 1986 above.

H. Fujioka: How did you avoid the effect of the change of the secondary emission characteristics of a material during irradiation?

F. Hohn: Do you find contamination a problem? I believe that unfortunately, contamination rates are high at low voltages.

J. Reimer: From your experience, what average percent error in a voltage measurement can you attribute to contamination build-up on the sample surface?

Authors: Contamination can be a problem but we have no specific means to combat it at this stage.

DC voltage level shifts of volts are possible but the level change is approximately linear with time and so can be corrected for relatively straightforwardly.

F. Hohn: In other spectrometers, the field of view is limited by the extraction field aberrations to about 0.5-1mm. Do you know of a design which does not suffer from this problem?

Authors: No.

M. Brunner: Have you experimentally observed positive charging caused by extraction grids? I found positive charging only with electrodes and not grids. The assumed explanation is that many of the electrons are reflected from the filter grid and return to the sample.

Authors: We have not conducted experiments as you suggest and if the explanation is correct we would expect it to depend on many factors including the nature of the sample, the operating point voltage and the mode of operation.

K.D. Herrmann: What is the effective working distance of the detector?

J. Reimer: What is the working distance of the e-beam probing system (final lens aperture to sample surface), as shown in Figure 4?

Authors: The physical working distance is 100mm but the electron optical working distance is electrically variable with the single pole lens.

K.D. Herrmann: How strong is the magnetic field at the sample and is any influence on the part expected?

Authors: The field strength is of the order of 70 milli-Tesla. Experiment and theory suggest that this field strength will have a minimal affect on a MOSFET.

K.D. Herrmann: Do ferromagnetic leads of the package affect the performance of the spectrometer?

Authors: Ferromagnetic leads can impair the image resolution but even then, measurements can be made on 1 micron tracks with little difficulty.

K.D. Herrmann: Has the magnetic field the form of a Glasers bell? How big is the FWHM?

Authors: The field has approximately the shape you describe from the top of the single pole lens and reduces to half the peak intensity in about 15mm (FWHM=30mm).

F. Hohn: More recently, "Time of flight" measurements for secondary electron analysis has been proposed. Do you know an extended paper on the subject and what is your opinion on it?

Authors: We believe that a time-of-flight approach could be an interesting avenue of research as a means of producing an open loop detector.

J. Reimer: What electron beam equipment did you use and what were the values for beam potential, beam current and beam diameter for your high-accuracy voltage measurements?

Authors: The SEM was a Cambridge Instruments S-200 operating with a beam voltage of 1-1.5 kV, spot size of 0.5 microns and beam current of the order of 1nA.

J. Reimer: Do you expect your electron detector to become commercially available? If so, when and for which SEM, or e-beam probing equipment?

Authors: We expect a detector based on the physical principles described here to be made commercially available in the near future.