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A DYNAMIC SINGLE E-BEAM SHORT/OPEN TESTING TECHNIQUE

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Abstract

Several electron beam techniques for electrical testing of interconnection modules have been presented by different authors in recent years. Most techniques use two or more electron beam energies to establish a charging and a non-loading reading mode. The present paper discusses the feasibility of employing the same beam energy for charging contact pads and reading pad potentials. This avoids the necessity of high voltage switching as used for altering the beam energy. A switching time of 100  $\mu$ s between 2 kV and 4 kV beam voltage which is restricted to this range has been reported earlier. Without switching, higher beam energies may be used with smaller transition times between charging and reading of the test pads.

Keywords: E-beam testing, short/open testing, printed circuit board, conductor network, packaging module, multi-chip package.

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Introduction

Chip packaging and interconnection technology has reached a state of miniaturization and wiring density in which mechanical contacting of the metal lines in a short/open test becomes crucial. Suitable probe heads are expensive and fragile and the mechanical test system is inflexible to packaging and design changes. Some effort has therefore been made to replace the mechanical probes by one or more electron beams (Engel and Holmstrom 1970; Engelke 1974; Gill et al. 1979; Hohn et al. 1982a,b; Pfeiffer et al. 1981; Pfeiffer 1982a,b; Sebeson 1973; Sebeson et al. 1973). Electron beams may be focussed on small contact pads and, with a suitable technique, may address the relevant measurement points under computer control. Interconnection modules having different part numbers may be tested with the same tool simply by loading corresponding design data, e.g. from a CAD-system,<sup>§</sup> into the test processor which allows maximum flexibility to design changes.

Contactless and computer-controlled test methods of this kind have been described by Hohn et al. (1982a,b) and Pfeiffer et al. (1981, 1982 a,b). In Hohn's technique the electron beam is deflected to impinge on one contact pad on the top side of the module (pad ① Fig. 1) in order to charge the addressed pad by electron bombardment. A high beam energy is used to produce a secondary plus backscattered yield of less than unity which gives rise to negative pad potentials. The charging of the addressed pad also causes the connected wiring to be charged to the negative

<sup>§</sup>CAD-system = computer assisted design system

List of symbols

$\Delta V$	Small pad voltage change due to charging in the read mode on all pads of one network	$\sigma_1$	Standard deviation of the detected electron rate from an uncharged pad
$\Delta V_i$	Small pad voltage change due to charging by one read pulse	$\sigma_2$	Standard deviation of the detected electron rate from a charged pad
$V_C$	Voltage to which a pad is charged by one charge pulse	$\sigma_{1,2}$	$\sigma_1$ or $\sigma_2$
$T_C$	Time required to charge a network to the voltage $V_C$	$n_S$	Threshold between detected electron rates on charged and uncharged pads
$K$	Number of pads on a module	$w_1$	Probability to detect more electrons than $n_S$ on an uncharged pad
$L_i$	Number of read cycles on pad $i$	$w_2$	Probability to detect fewer electrons than $n_S$ on a charged pad
$V_R$	Voltage to which charging is tolerated in the read mode	$f_1(n)$	Distribution of the detected electron rate on an uncharged pad
$V_G$	Voltage of uncharged pads, e.g. ground potential	$f_2(n)$	Distribution of the detected electron rate on a charged pad
$V_S$	Threshold voltage between charged and uncharged pads	$S$	Mean signal difference between charged and uncharged pads
$T_R$	Read time given by one read pulse	$I_P$	Primary beam current hitting a pad
$\epsilon_1$	Detected portion of secondary electrons emitted from an uncharged pad taking geometrical effects and retarding fields into account	$n_1$	Number of detected electrons from an uncharged pad
$\epsilon_2$	Detected portion of secondary electrons emitted from a charged pad taking geometrical effects and retarding fields into account	$\bar{n}_1$	Mean number of detected electrons from an uncharged pad
$\epsilon_{1,2}$	$\epsilon_1$ or $\epsilon_2$	$n_2$	Number of detected electrons from a charged pad
$\delta$	Secondary electron yield	$\bar{n}_2$	Mean number of detected electrons from a charged pad
$N$	Number of incident primary electrons	$n_{1,2}$	$n_1$ or $n_2$
$\sigma$	Standard deviation of the detected electron rate	$\bar{n}_{1,2}$	$\bar{n}_1$ or $\bar{n}_2$

voltage (pads ③, ④ in Fig. 1). Erroneously connected wiring, e.g., due to shorts (pads ⑤, ⑥ in Fig. 1), also acquires this negative potential while disconnected parts of open circuits remain unchanged (pad ② in Fig. 1). Opens and shorts are thus indicated by the resulting potential change on all pads due to the charging of one pad. The potentials are sensed in this testing technique by addressing the pads with the electron beam and evaluating the secondary electron energy shift. A spectrometer-detector system is used for this purpose. Charging effects during the potential read mode have to be avoided. This is achieved in Hohn's technique by reducing the

beam energy during the read phase to the value of equilibrium between incident and emitted currents. The low energy beam addresses pads ②, ③, ④, ⑤, ⑥, ⑦ in the example shown in Fig. 1 in order to read the resulting potentials. Hohn suggests the use of an additional third beam energy below the value of equilibrium to achieve positive charging in testing through-connections.

Pfeiffer's technique follows a similar testing sequence using a charging flood beam and a discharging stepping beam but with selective discharging. Charging and discharging beams have different energies.

Both techniques thus change the electron beam energy during the test either by high voltage switching as in Hohn's technique or by using multiple beams as in Pfeiffer's technique. This poses an engineering challenge in electron optics and electronics. For technical and economical reasons it appears desirable to avoid the necessity of multiple beam energies.

Principle of dynamic e-beam short/open testing

The general testing strategy using the dynamic e-beam method as suggested in this paper is similar to the technique described by Hohn et al. (1982a,b) but avoids switching electron beam energies. The electron beam is first deflected to impinge on a contact pad in order to charge the addressed pad together with the electrically-connected circuitry. The beam energy is set to yield negative charging. The voltage to which the pad charges may be controlled by evaluating the secondary signal during the process of charging.

The same beam energy is used to sense the pad potentials by secondary electron detection in the read mode. During this mode only insignificant pad potential changes  $\Delta V$  due to charging are allowed  $\Delta V \ll V_C$ . Let the network have  $K$  pads and pad  $i$  be addressed  $L_i$  times in the read phase. For the inspection of each pad  $\Delta V_i \ll V_C / \sum L_i$  is therefore required to avoid charging.

In practice some voltage change may be tolerated as long as it stays below a critical limit  $V_R$  (Fig. 2).  $V_C$  is the voltage of a charged pad and  $V_G$  is measured on uncharged pad (e.g.  $V_G =$  ground potential). A threshold voltage may be defined between both,

$$\text{e.g. } V_S = \frac{2}{3}(V_C - V_G) \quad (1)$$

to allow for discrimination between charged and uncharged pads in the measurements. Charging in the read phase may be allowed up to  $V_R = (V_C - V_G)/3$ . This leaves a tolerance of  $(V_C - V_G)/3$  for each pad, charged or uncharged, to allow for voltage variations among pads or voltage measurement errors due to noise fluctuations (Fig. 2).

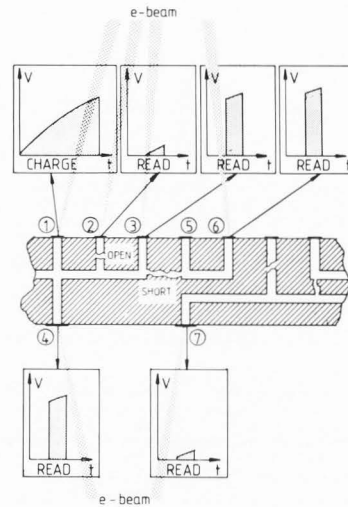


Fig.1: Principle of dynamic short/open e-beam testing. Charging on pad ① and subsequent reading on pads ② through ⑦ by deflecting the electron beam reveals potentials as indicated. The missing high potential on ② indicates an open while the unexpected potential on ⑤ and ⑥ is caused by a short.

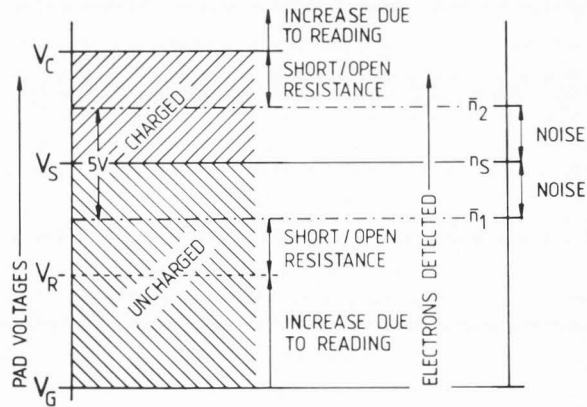


Fig.2: Classification of the pad potentials to distinguish between charged and uncharged pads.  $\bar{n}_1$  is the largest mean number of secondary electrons detected on an uncharged pad after consideration of all relevant voltage variations.  $\bar{n}_2$  is the correspondingly smallest mean number of secondary electrons on a charged pad. The signals, corresponding to  $n_1$  (uncharged) and  $n_2$  (charged) should not overlap due to noise. This imposes conditions for the minimum numbers of  $\bar{n}_1$  and  $\bar{n}_2$ , respectively.

Voltage variations may occur due to different resistances of shorts and opens (Brunner et al., 1984). A time  $T_C$  is needed to charge a pad and the connected wiring to a potential  $V_C$  depending on the capacitance of the network and the beam current. Since the voltage increase with time is approximately linear in the range of interest, which is well below the equilibrium pad potential (Brunner, 1984), a read time of

$$T_R < \frac{1}{3} \frac{T_C}{\sum_{i=1}^K L_i} \quad (2)$$

meets the requirements stated above. The longest read time to avoid charging seems to drop as the number of pads to be tested increases. On the other hand the charge time  $T_C$  along with the capacitance of the network increases with increasing numbers of pads. The limitation of  $T_R$  with an increasing number of pads  $K$  is thus less critical.

The following calculation illustrates a realistic example: A network has a capacitance of 1 pF and consists of 10 pads which are to be probed twice each, once before and once after charging. With an effective charging current of  $10^{-6}$  A as the balance between primary, backscattered, and secondary currents, this network is charged to -10 V within

$$T_C = \frac{UC}{I} = 10 \mu s \quad (3)$$

The read time in this case is limited due to eq. (2) to

$$T_R = 166 \text{ ns} \quad (4)$$

Different currents, capacitances, and voltages leading to longer charging times have been used in the experiments because of technical limitations imposed by the present setup.

#### Testing reliability and noise considerations

The lowest limit of the read pulse duration is given by the smallest signal-to-noise ratio which still allows reliable discrimination between

charged and uncharged pads. The signal of interest in the testing technique is the difference of the signals detected from charged and uncharged pads. The detected signals may be assumed proportional to the number of electrons hitting the detector. If  $N$  primary electrons impinge on a charged pad (voltage  $V_C$ ) a mean number of secondaries  $\bar{n}_2 = \epsilon_2 \delta N$  will be detected ( $\delta$  = emission yield),  $\epsilon_2$  describes the collection efficiency including the filtering of the retarding analyzer grid. On an uncharged pad (voltage  $\leq V_R$ ) a correspondingly smaller mean number  $\bar{n}_1 = \epsilon_1 \delta N$  of secondaries will be detected, since the spectrometer rejects more electrons leaving the portion  $\epsilon_1$  to be detected.

Experiments show that from pads with at least 5 V =  $V_C - V_R$  potential difference

$$\bar{n}_2 \geq 2 \bar{n}_1 \quad \text{and} \quad \epsilon_2 \geq 2 \epsilon_1 \quad (5)$$

are readily obtained. Voltage fluctuations due to different resistances of opens and shorts result in 5 V being the smallest voltage difference to yield eq. (5). The equals sign in eq. (5) yields a signal difference between charged and uncharged pads of at least  $(1/2)\bar{n}_2$  or  $\bar{n}_1$ .

Testing reliability considerations determine the tolerable noise of the signals in the following way: Fluctuations cause a statistical distribution of values  $n_1$  and  $n_2$  to be measured which deviates from the mean values with a variance of  $\sigma^2 = (n_{1,2} - \bar{n}_{1,2})^2$ . A threshold  $n_S$  may be defined at  $n_S = (\bar{n}_2 - \bar{n}_1)/2$  in consistence with eq. 1 if a linear dependence exists between the pad voltages and detected electron numbers to distinguish between charged pads (Fig. 3):  $n > n_S$  and uncharged pads:  $n < n_S$ . Some  $n_2$  values measured on charged pads will incidentally be smaller than the threshold value  $n_2 < n_S$  due to noise fluctuations, thus leading to a measurement error.  $n_1 > n_S$  causes a corresponding measurement error on uncharged pads. If voltages on 30,000 pads are to be measured on each module and one measurement error is allowed among 30,000 modules then a total error rate of less than  $10^{-9}$  is required.

The probability  $w_2$  for a measurement error on a charged pad is given directly by the hatched area under the probability distribution curve in Fig. 3 which extends beneath the threshold. The error rate  $w_1$  on uncharged pads is given by the dotted area.

$$w_2(n_2 < n_S) = \int_{-\infty}^{n_S} f_2(n) dn \quad (6)$$

$$w_1(n_1 > n_S) = \int_{n_S}^{\infty} f_1(n) dn$$

To provide an approximation for the distribution  $f_{1,2}(n)$  they may be assumed Gaussian with mean values  $\bar{n}_{1,2}$ :

$$f_{1,2}(n) = \frac{1}{\sqrt{2\pi}\sigma_{1,2}} \exp\left[-\frac{(n - \bar{n}_{1,2})^2}{2\sigma_{1,2}^2}\right] \quad (7)$$

The standard deviations  $\sigma_{1,2}$  at the detector are composed of the fluctuations in both primary current and secondary electron production (Shockley and Pierce, 1938; Everhart et al., 1959; Baumann and Reimer, 1981)

$$\sigma_{1,2} = \delta \sqrt{\epsilon_{1,2}(1+b)N} \quad (8)$$

where  $\delta$  is the secondary emission yield,  $b$  is between 4 and 10 at 10 keV (Reimer, 1971) depending on the pad material,  $N$  is the number of incident electrons, and  $\epsilon_{1,2}$  are the detected portions of the secondary electrons.

The evaluations of the integrals eq. (6) are tabulated in relevant publications on statistics (e.g. Hartung, 1982) and yield the required error rate of  $10^{-9}$  by integrating over the tails in Fig. 3 up to six times the standard deviation  $\sigma$ . The threshold  $n_S$  is therefore required to be outside of the  $6\sigma$  limit.

$$\int_{-\infty}^{[n_S = \bar{n}_2 - 6\sigma]} f_2(n) dn \approx 10^{-9}$$

$$\int_{[n_S = \bar{n}_1 + 6\sigma]}^{\infty} f_1(n) dn \approx 10^{-9}$$

A signal difference between charged and uncharged pads  $S = (\bar{n}_2 - \bar{n}_1)$  of about  $12\sigma$  is thus required which yields a minimal signal-to-noise ratio of  $S/\sigma = 12$  for an error rate of less than  $10^{-9}$ . An additional factor of 3 in the signal-to-noise ratio allows for noise contributions from the detection system (Baumann and Reimer, 1981).

$$\frac{S}{\sigma} = 3 \cdot 12 = 36 \quad (9)$$

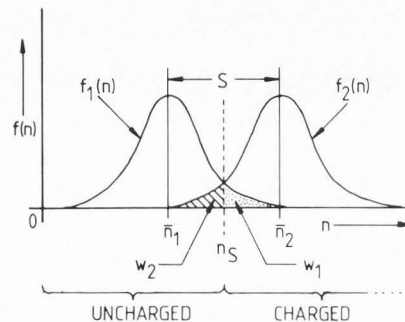


Fig.3: Statistical distributions of detected electrons with mean numbers  $\bar{n}_2$  on a charged pad and  $\bar{n}_1$  on an uncharged pad. Probabilities  $w_1$  and  $w_2$  of erroneous detection of a number of electrons beneath the threshold  $n_S$  on a charged pad and of erroneous detection of a number of electrons above the threshold on uncharged pads are represented by the marked areas.

The smallest read beam pulse duration may be calculated from this signal-to-noise requirement. Eq. (9) together with eqs. (5) and (8) yield equations for the required number of primary electrons  $N$ :

$$\frac{S}{\sigma} = \frac{\frac{1}{2}\epsilon_2 \delta N}{3\delta\sqrt{\epsilon_2 N}} = \frac{1}{6}\sqrt{\epsilon_2 N} = 36 \quad (10)$$

$$\frac{S}{\sigma} = \frac{\epsilon_1 \delta N}{3\delta\sqrt{\epsilon_1 N}} = \frac{1}{3}\sqrt{\epsilon_1 N} = 36$$

In eq. (8)  $b = 8$  has been assumed. The collection efficiency of the detector may be assumed to be  $\epsilon_2 = 0.1$  and  $\epsilon_1 = 0.05$  for secondary electrons emitted from charged and uncharged pads respectively. A number  $N = 4.7 \cdot 10^5$  primary electrons on charged pads and  $N = 2.3 \cdot 10^5$  on uncharged pads is thus required according to eq. (10) to meet the signal-to-noise requirements.

The smallest read pulse duration to provide  $N = 4.7 \cdot 10^5$  electrons with a beam current of  $I_P = 10^{-6}$  A is calculated to be  $T_R = 75$  ns where  $T_R = I_P/N$ . This is well below the value of 166 ns which is required to avoid excessive charging (eq. 4).

#### Feasibility experiments

The aim of the experiments was to 1) verify the theoretical charging characteristics, 2) demonstrate that excessive charging can be avoided in the read mode by ensuring a short read pulse duration, and 3) show that network discharge by leakage does not disturb the function of the test. A ceramic module which interconnects 12 integrated circuits with hybrid circuitry served as a sample for the experiments. The metal lines and pads were gold coated. The sample was mounted on the specimen stage of a scanning electron microscope in a tilted position of  $40^\circ$ . The voltage contrast was optimized by tilting since no energy-analyzing detector was used. The signals obtained for different pad voltages were calibrated by applying external voltages to the pads. The secondary signal was doubled by applying -100 V. The specimen current on the pads which is the effective charging current in the experiments was measured to be about  $10^{-8}$  A with or without -100 V applied to the pads.

The scanning microscope was equipped with a blanking system and a charge neutralizing argon ion gun. The ion gun allowed positioning of the sample pads under the beam without charging effects when the microscope was operated at 10 kV. The ion gun was not operated during the charging experiments.

Fig. 4 shows an SEM image recorded from the ceramic interconnection module with 10 keV electrons and neutralization by 1 keV argon ions. The noise in the image results from instabilities of the gas discharge in the ion gun but these have no influence on the function of the test. The electron beam was positioned in spot mode on pad ①. The ion gun was switched off after blanking the electron beam. The e-beam was subsequently switched on to charge the pad.

The resulting detector signal increase, which was recorded in a storage oscilloscope, is shown in Fig. 5a. The analogous result of charging pad ② is shown in Fig. 5b. Pad ① is thus charged to -100 V within approximately 200 ms while the same process on pad ② takes 40 ms due to different network capacitances.

The capacitances of the pads and the corresponding networks were measured by a capacitance bridge to be 25 pF on pad ① and 3.5 pF on pad ②. According to eq. (3), pad ① should be charged within 250 ms and pad ② in 35 ms, which is in good agreement with the experimental results.

A series of 10 e-beam pulses, each with a duration of 150  $\mu$ s and an electron energy of 10 keV, was used to detect the potential on pad ② which was previously charged. The resulting signals superimpose on each other to form the upper curve in Fig. 6. No voltage change can be observed during the measurement due to the short pulse duration although the read beam energy is set to cause negative charging. The pad was subsequently discharged by the ion beam to measure the secondary signal in the uncharged state. Three pulses are superimposed to form the lower curve. Another 32 pulses were injected but only the signals appearing during the last two pulses were recorded. These two curves show a small increase in the pad potential but still allow an excellent discrimination between charged and uncharged pads. This result demonstrates that reliable voltage detection with short 10 keV e-beam pulses is possible without excessive charging. From eq. (2) about 89 read pulses of 150  $\mu$ s duration would be allowed.

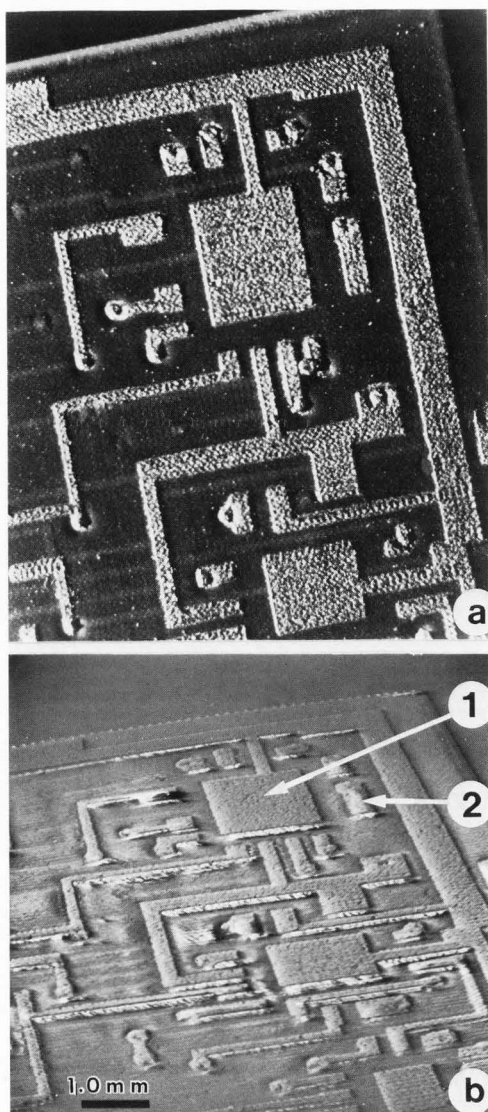


Fig.4: a) Photograph of a ceramic interconnection module used in hybrid circuitry as obtained in an optical microscope. b) SEM-image of the same module with 10 keV electrons and ion charge neutralization, specimen tilted by  $45^\circ$ . Two test pads are marked.

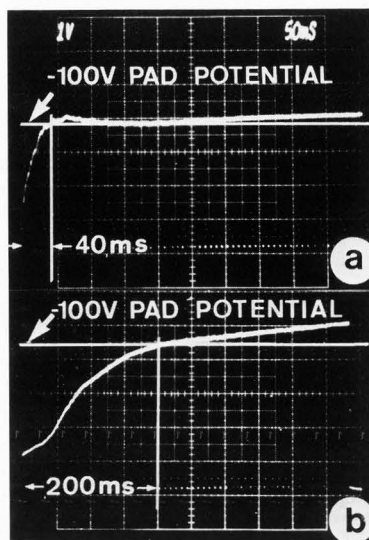


Fig.5: Increase of the detector signal with dwell time of the 10 keV electron beam on a) pad 2 and b) pad 1. Different time constants due to inherent network capacitances.

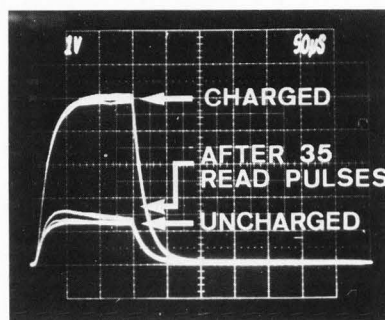


Fig.6: Reading signals on charged and uncharged pads obtained by the 10 keV electron beam. The signals on charged as well as uncharged pads do not change by disturbing amounts due to charging by the read beam.

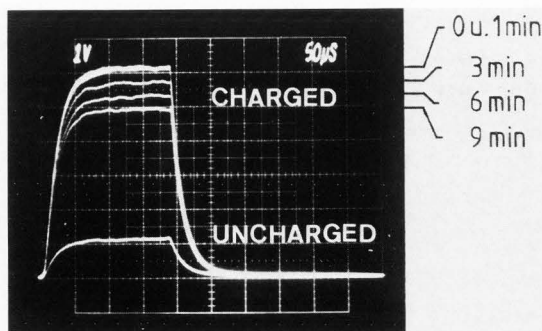


Fig.7: Discharging of a charged pad due to leakage currents. No disturbing voltage drop in several minutes.



The charge storage time in a network was measured in the following experiment (Fig. 7). The voltage of pad ② was measured immediately and in a sequence of time intervals after charging. The voltage drop can be seen to remain below an acceptable limit for 3 to 6 minutes. The lower curve represents the uncharged signal.

#### Conclusion

An electron beam short/open testing technique which avoids switching of the beam voltage has been described. This method suppresses charging in the read mode by short read pulse durations. Reliability and noise considerations indicate that reliable voltage measurements with an error rate below  $10^{-9}$  are possible with pulse durations being adequate for tolerable charging. Experiments confirm the calculated charging characteristics. It is demonstrated that voltage detection is possible with a 10 keV electron beam without disturbing charging effects. Decay of the charge stored in a network is found not to be significant within about five minutes.

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Discussion with Reviewers

F.J. Hohn: How can sample insulator charging be avoided during the registration and/or during mapping of a distorted sample? Does the use of a discharging flood ion beam generate surface potentials of varying magnitude?

Does the introduced voltage (e.g. -100 V) pose any problem when reading adjacent pads - local field effects?

Authors: These questions are subject to present investigations.

F.J. Hohn: The timing relation between charging, reading, and discharging during read is not quite clear from formulas 2-4, is the effective charging current  $10^{-6}$  A or less?

Authors: There is no discharging but only charging during the charge mode as well as during the read mode. Equation 2 represents the general requirement for tolerable charging while equations 3 and 4 describe an example assuming a charging current of  $10^{-6}$  A.

F.J. Hohn: What do you mean when mentioning that:  $E_2$  describes the collection efficiency including the filtering of the retarding analyzer grid? Is this the voltage resolution of the analyzer? If so, what are the characteristics of it?

Authors: It does not say  $E_2$  but  $\epsilon_2$  which is the portion of emitted secondary electrons hitting the scintillator.  $\epsilon_2$  describes the filtering of the retarding grid because the rejection of electrons lowers the detected portion.

F.J. Hohn: Do you know of any secondary electron detector scintillator-PMT with rise times of a few ns as required for 150 ns read pulses?

Authors: A rise time of a few ns is not required which is a fact known from electron beam integrated circuit testing. Pulses of less than 1 ns duration are used in this technique with regular scintillator-PMT detection.

F.J. Hohn: What is the relation between charging time and beam current? Assuming a primary beam current increase of two orders of magnitude, does the charge time reduce accordingly under the same experimental conditions?

Authors: Yes.

F.J. Hohn: What influence on charge time has an increase in beam potential?

Authors: A higher beam potential increases the injected current since the emission yield drops. This results in a shorter charge time.

S. Görlich: What is the shortest pulse time acceptable for detecting a reading signal and a subsequent reliable short/open decision?

Authors: This depends on the required reliability. If  $10^{-9}$  is the tolerated error rate of the technique and the primary beam current is  $10^{-6}$  A the shortest pulse duration calculates to 75 ns as outlined in the paper.

S. Görlich: What will be the overall measuring time for a whole interconnection module using the described technique?

Authors: On a module containing 30,000 pads the charge and read times sum up to less than 1 min. Additional time has to be allowed for load/unload, registration and computer processing.

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