INITIAL EXPERIMENTS ON VC FOR PARAMETER SELECTION
3.0 INTRODUCTION

As discussed earlier the aim of this project is to use the Electron beam as a tool for testing the ICs, and to apply IP techniques to the acquired SEM images of ICs for fault inspection. In the last chapter, development of a full-fledged system for this purpose is discussed. The main object there is to discuss the hardware development for IP. In this chapter, the experiments done to know about the e-beam interaction with materials, and VC phenomenon, are reported. These experiments further helped in deciding the experimental parameters for use while acquiring VC images.

Two specimens are chosen for this purpose, i) flat specimen - a thick film RC network and ii) angular specimen - a metal ball (0.55 mm dia). A metal ball is chosen for studying VC effects at various angles.

3.1 ARRANGEMENT OF EXPERIMENTAL SETUP

For mounting the angular specimen a sample holder is chosen, which could be given bias. The metal ball is stuck to the sample holder using silver paste. The flat specimen is mounted in a chamber on a ZIF socket as described in article 2.4. (See Fig.2.14). The experimental arrangement is discussed next.

3.1.1 For the flat specimen

Fig.3.1 shows the two hybrid circuits out of which one having bonded pins for connection is chosen for experiments on flat specimen. It consists of a capacitor indicated by two parallel lines. The next two English 'C' type structures are the hybrid resistors. This circuit is made on Alumina substrate with
Fig. 3.1: Photograph of two thick film hybrid circuits mounted on ZIF socket.
Bismuth Ruthinate as resistor material and Pd-Ag as conductor. One of the resistors between pin 13 and 15 (marked in Fig.3.1) in this hybrid circuit is chosen for VC studies and therefore is fractured by passing high current through it. "0" bias is applied to pin 13 and negative bias between 0V and -10V is applied to pin 15.

3.1.2 For the angular specimen

A stainless steel spherical ball of diameter 0.55 mm is selected as an angular specimen because on the equator of this spherical ball, a complete range of angles from -90° to +90° becomes available. Shifting the e-beam to be incident along the equator could amount to changing the angle of incidence. The experimental arrangement (not shown in Fig.3.2a) is shown in Fig.3.2a. The sample (ball) is biased positively in the range 0V to +20V with respect to ground. The angle dependence of different parameters like edge effect, accelerating voltage, bias voltage is measured using the line scan across the sphere and recording the video on CRO. Fig.3.2b shows the photograph of a line scan stored on a Gould storage oscilloscope (Type D.S.). The horizontal scale of the oscilloscope is calibrated in terms of angle. In the line scan waveform, the leftmost peak corresponds to one edge of the sphere i.e. -90° angle and the right most peak corresponds to the other edge of the sphere i.e. +90°. Normal incidence of the primary beam is considered as the 0° angle of incidence with respect to specimen surface. As can be seen from Fig.3.2b, the scan is observed over 7.5 cm on oscilloscope. Hence each division corresponds to 24°. VC observations are recorded for various
Fig. 3.2: (a) Experimental setup for angular specimen.
Fig. 3.2 (b): Secondary emission from angular specimen.
applied bias, angle of incidence and beam energy. More number of observations are taken in the range 0-2V as the VC appeared to change its monotony in this range. 

3.2 THE SE AND BSE IMAGES

As seen in the first chapter (article 1.4), the interaction of θ-beam with any specimen surface gives rise to a number of electrons with different properties. However as far as our application of surface study is concerned, only two types of electrons are of interest, namely SE and BSE. S.Kimoto and H.Hashimoto in 1968 have studied the SE and BSEs comparatively. They have reported that the SE image can show a potential distribution on a specimen surface, but the BSE image cannot. They have studied this behaviour for a transistor in an IC, under a condition of reverse bias voltage between the collector and base. Here the effect of VC on these two types of electrons and their resulting images will be discussed.

Fig.3.3 shows the SEM micrographs of the hybrid resistor around the fracture region. Fig.3.3a shows the BSE image with bias applied which indicates some material contrast between the resistance paste and the conductor materials. Fig.3.3b is the SE image showing mainly topographic details, without bias applied. Fig.3.3c shows the SE image of the fracture in the resistor material, with bias applied, which is normally called as VC image, indicating clearly the fracture.

Similar observation with the sphere is reported in the micrographs in Fig.3.4. Line scans on Fig.3.4a and b respectively, show the observed variation of SE and BSE at
Fig. 3.3: SEM micrograph of a fracture in thick film hybrid circuit
   (b) unbiased SE image
   (a) biased BSE image
Fig. 3.3 (c): SEM micrograph of a fracture in thick film hybrid circuit showing biased S.E. i.e. VC image.
various applied bias voltges. Comparison of the line scans on the sphere in SE (Fig.3.4a) and BSE (Fig.3.4b) images can be made for different applied bias. All the linescans in Fig.3.4a show two peaks with the left hand side peak at a higher amplitude as compared to the right hand side peak. Further the peak heights on both sides are decreasing with increase in voltage bias. This behaviour is not found in the BSE image in Fig.3.4b. All the linescans show a single peak on the left hand side. The peak height is constant. It could be seen that the left hand side intensity of the peak near the edge has remained constant in BSE image while its changes are observed in case of SE image with applied bias.

This clearly indicates that VC is observed only in case of SE emission. Therefore further study in the experiments on VC is restricted to SE images only.

3.3 THE EDGE EFFECT

S.Kimoto and H.Hashimoto have studied this phenomenon in 1968. In an SE image of a metal fracture, they have noticed that extreme brightness occurs at a ridge and protruding parts. They have given a reason that an electrostatic field caused by the potential supplied to the accelerating electrode of the detector reaches to the surface of the specimen. The field is not uniform in case of specimen with edges and valleys. Therefore the yield of the SE is increased by a stronger field at the edge and other protruding parts.

Fig.3.4a indicates the edge effect. The emission from the left hand side is more prominent than on the right hand side.
Fig. 3.4: SEM micrograph of
a) SE image of a sphere
b) BSE image of a sphere
This is mainly due to the presence of the SE collector (PMT) on left hand side which efficiently collects the SE when the beam is incident on left part of the sphere in Fig.3.4a. The SEs emitted on the right hand side possess slightly lower probability of reaching the collector.

Most of the SEs have energy between 2-3 eV. These electrons being weak in energy become more sensitive to the equipotentials formed outside the sphere. At higher bias the SEs, which contribute to the VC signal, have higher energies and get less affected by the outside distribution of potentials giving rise to lower difference between two maxima in Fig.3.5.

It is observed from the SE image of the sphere that the difference between maximum and minimum voltage contrast (VC) seen from line-scan decreases for higher applied bias. Fig.3.5 shows this difference \((V_{\text{max}} - V_{\text{min}})\) with respect to applied bias at different beam energies. In Fig.3.5, the fall of edge effect with bias can be clearly seen. The decrease in edge effect with bias voltage appears to be more uniform for accelerating voltage 2.5KV. The edge effect is lesser at higher voltage and for ICs with a choice of higher voltage between 4V and 6V, selection of 6V bias can be done.

### 3.4 NONLINEARITY IN VOLTAGE CONTRAST

VC images of thick film fractured sample (described in article 3.1.1), at various bias voltages are taken. As can be observed from Fig.3.6a,b,c, and d, there is definite qualitative change in grey shades with change in bias. Maximum contrast can be seen in Fig.3.6d at -10V bias and uniform intensity can be
For different accelerating voltages.

Figure 3.5: Variation of $V_{max}$ and $V_{min}$ with difference in applied bias.
Fig. 3.6: Voltage contrast observed across the fracture with
a) no bias applied
b) -3V bias
Voltage contrast observed across the fracture with Fig. 3.6:

(c) -6V bias
(d) - 10V bias
observed at no bias in Fig.3.6a, with variation of contrast for in-between bias voltages.

Quantitative measurements are also taken to study the nonlinearity in the VC. For this purpose, as mentioned in the article 3.1.2, the SEM video output is fed to the Gould storage oscilloscope (Type D.S.). The SEM video output is a TV signal, with its peak representing the SE signal from the PMT. Thus variation in SE emission amounts to occurrence of valleys and peaks in the video signal. When the e-beam is positioned at a point and the video output is measured, it represents SE emission at that point on the specimen. Output on oscilloscope at zero bias is taken as reference. Depending on topography the waveform at zero bias has corresponding peaks and valleys. Certain points on this curve are chosen. Then with applied bias, the change in intensity (or amplitude) at these selected points is noted down. These readings are normalized with respect to zero bias readings. These normalized readings are taken as quantitative measure of voltage contrast. The voltage contrast variation with bias voltage is plotted and shown in Fig.3.7 with circles indicating observed values of VC for different bias voltages. It is clear that VC varies nonlinearly with applied bias and after about 7V of bias, it saturates.

The VC phenomenon is also studied for the spherical metal ball sample. Figs.3.8a and b give the dependence of the observed voltage contrast on the input bias voltage for different angles of incidence and beam accelerating voltages. It can be seen that as the positive input bias voltage is increased, the VC
Fig. 3.7: Curve fitting method to remove nonlinearity in voltage contrast data.
Fig. 3.8: Non-linearity in voltage contrast in angular specimen
(a) Voltage contrast variation in bias for different accelerating voltages.
(b) Voltage contrast variation in bias for different angles.
decreases. This is in accordance with the VC principle²²,²⁷. Fig.3.8a shows curves drawn for angle -6⁰, +6⁰ and +54⁰. These angles are chosen to depict the representative behaviour of VC with bias for different angles. For all the angles, the maximum VC (VC_max) is observed between 1 to 2.5V. However this VC_max is comparatively higher for 6⁰ angle compared to the other angles. Therefore the angle of 6⁰ is chosen for the further experiments on VC.

The curves in Fig.3.8b depict the variation of VC with input bias for accelerating voltages 2.0KV, 2.5KV and 5.0KV. The angle of observation is 6⁰. For all the accelerating voltages, the VC goes through a maximum between the bias voltages of 1 to 2.5V. Further, it can be seen that VC_max is higher for accelerating voltage = 2.5KV. At other bias voltages also the curve corresponding to 2.5KV shows higher VC values. Therefore for further experiments, 2.5KV is fixed as accelerating voltage.

From the above discussion, the selected angle and voltage bias for VC measurements come out to be 6⁰ and between 1 to 2.5V respectively. Now since the normally used voltage in IC is upto 5.5V and since the VC observed at an angle of 6⁰ is larger than other two angles for all the voltages, the voltage is chosen for further experiments is approximately 6V.

3.4.1 Removal of nonlinearity using software

The VC phenomenon is used for testing IC performance. The nonlinearity in VC may introduce errors in the measurements of voltage or voltage distribution on the chip. For example, consider a digital IC. Its performance could be explained in
terms of two logic levels '0' and '1'. Depending on the family of the IC, there is a restriction on the voltages corresponding to these two levels, e.g. in case of a TTL IC, a logic '0' level corresponds to 0V to 0.8V and a logic '1' level corresponds to 2.4V to 5.0V. The nonlinearity in VC can detect the logic '0' and '1' levels. But near the maximum of '0' level and near the minimum of '1' level, if the measured VC does not correspond to exact value, then the performance of the IC might be misinterpreted. For example, because of nonlinearity, it may be possible that, a 1.5V reading of VC which is the tristate, could be measured as say 2.5V and then the state may be interpreted as logic '1' state. Therefore it becomes necessary to remove the nonlinearity in VC measurement.

Removal of VC nonlinearity could be done using either hardware or software. Linearisation of VC by hardware method has been tried by Gopinath and Sanger in 1970. They have used a retarding grid held at a potential varied using a hardware negative feedback loop, to retain the signal output from the analyser constant. The feedback signal to the retarding grid is a linear function of the local potential.

Fujioka et al in 1978, have used a software method to linearise the VC output. They have applied a +5V triangular signal and measured the output, which is nonlinear, by an oscilloscope. The difference between triangular input and nonlinear output curves is stored in the memory in the computer. This data is used to linearise and calibrate SEM VC signals.

A method based on curve fitting by software is reported here, which as per the author's knowledge is not reported till
now. The method developed here is used to linearise the nonlinear data obtained on fractured thick film sample. A curve fitting program in FORTRAN-77 based on least squares method is used for this purpose. This program enquires for the expected accuracy and gives the best polynomial fit for that particular accuracy. In the case of the data plotted in Fig.3.7, a polynomial of order 5 is best fitted. The fitted values are marked by a triangle in Fig.3.7. The relation between applied voltage (AV) and the Observed VC signal (OV) is found to be:

\[ OV = B_0 + B_1 \cdot AV^1 + B_2 \cdot AV^2 + B_3 \cdot AV^3 + B_4 \cdot AV^4 + B_5 \cdot AV^5 \]

where \( B_0, B_1, B_2, B_3, B_4, B_5 \) are constants. With the maximum percentage error of 3.6938 %, the values of these constants are found to be \( B_0 = 0.3312988, B_1 = 0.2080078, B_2 = 0.2949219, B_3 = -0.1024170, B_4 = 1.2832642E-02, B_5 = -5.5980682E-04 \). Using the above values of the constants a Correction Factor (CF) is found as \( CF = B_2 \cdot AV^2 + B_3 \cdot AV^3 + B_4 \cdot AV^4 + B_5 \cdot AV^5 \). The corrected values are plotted in Fig.3.7, marked by a cross (x).

Thus a linear relation would be obtained with \( B_0 \) as the intercept on the Observed VC (OV) axis. This indicates that possibly the topography and material contrast are not eliminated. \( B_1 \) would be the slope of this line. The corrected VC would be \( VC' = VC - CF \). After storing the coefficients in memory of the computer, the correction can be applied for any particular value of bias voltage and exact node voltage can be predicted.

The developed method appears to be much better than that by Fujioka et al.\(^2\), since there is a curve fitting approach involved in our method. Fujioka has taken only a single triangular wave.
with amplitude 5V. In the developed method measurement of amplitudes at a point for 0V to -10V is done. This makes it possible to apply the method to positive range of bias voltages and to any amplitude. This approach is unconditional and because of its curve fitting nature, more reliable, unlike Fujioka's approach where he stores only one standard waveform and calibrates the output based on them.

3.5 DEPENDENCE OF VC ON ENERGY

VC images of fractured thick film samples at different accelerating voltages are taken and the micrographs obtained are shown in Fig.3.9. Figs.3.9a, b, and c show the micrographs taken at 2.5 KV, 5KV and 12.5kV accelerating voltages. Qualitative change is observed in these images. In Fig.3.9a, the contrast on the two sides 1 and 2 of the fracture, appears to be less as compared to that in Fig.3.9b. Again the contrast appears to be decreased in Fig.3.9c. Thus qualitatively, one can say that there is an increase in contrast while going from 2.5KV accelerating voltage onwards and a decrease after 5.0KV. The line scan superimposed on the micrographs indicates the variation in the scan amplitude at different points. The scan amplitude appears to be more for accelerating voltage of 5KV (see Fig.3.9b). The biased portion looks brighter as compared to that in Fig.3.9a for accelerating voltage 2.5 KV. However this scan amplitude seems to be decreased at 12.5KV accelerating voltage in Fig.3.9c. The biased portion appears darker as compared to that in Fig.3.9b. Thus there is a peak in VC from 2.5 KV to 5KV and a decrease thereafter.
Fig. 3.9: Variation of VC with different accelerating voltages across a fracture in thick film hybrid circuit.

a) 2.5 KV,  b) 5.0 KV.
Fig.3.9 (c) : Variation of VC with 12.5 KV accelerating voltage across a fracture in thick film hybrid circuits.
A quantitative measurement of dependence of VC on energy is done for the spherical ball sample. The curves in Fig.3.10a represent variation of VC (normalised with respect to VC at 0V bias) with accelerating voltages. The curves are plotted for different angles (-66°, 6°, 54°), at 6V bias. The decrease in VC with $\text{VC}_{\text{max}}$ at about 2.5KV accelerating voltage for all the angles, can be seen from the graph for this angular sample as well. The $\text{VC}_{\text{max}}$ for angle $= 6^0$ appears to be higher in this case. This $\text{VC}_{\text{max}}$ occurs around 2.5KV accelerating voltage.

In Fig.3.10b, variation of VC with accelerating voltage is plotted for a fixed angle ($=6^0$) for bias voltages 2V, 4V and 6V. $\text{VC}_{\text{max}}$ occurs around 2.5KV accelerating voltage. This supports the selection of 2.5KV, as explained in article 3.1.1 as the accelerating voltage for experiments.

3.6 DEPENDENCE OF VC ON ANGLE OF INCIDENCE

The line scans superimposed on the micrograph in Fig.3.4a, indicate the dependence of VC on angle of incident beam. The normalised VC is calculated from Fig.3.4a, Fig.3.11a shows its variation with angle of incidence at various accelerating voltages for voltages =6V and Fig.3.11b shows variation of VC with angle of incidence at various bias voltages for fixed accelerating voltage = 2.5KV.

In Fig.3.11a, the dependence of VC on angle of incidence can be clearly seen. All the curves show maximum VC at angle=$6^0$, which is almost flat surface. Thus previous selection of angle is confirmed. The VC decreases with increasing bias, and the maximum of $\text{VC}_{\text{max}}$ is obtained for 2V bias. But as explained before and as
Fig. 3.10: Variation in VC with accelerating voltage in angular specimen at (a) different angles (b) different biases
Fig. 3.11: Variation in VC with angle at (a) different biases (b) different accelerating voltages.
required for IC testing bias voltage of 6V is chosen.

As can be seen from Fig.3.11b, $V_{C_{\text{max}}}$ for the accelerating voltage 2.5KV and 5KV occurs at angle 6°. However the curve for accelerating voltage 2.0KV shows anomalous behaviour. It shows a peak for angle = 30°. Considering previous discussions in article 3.5, along with these results, selection of accelerating voltage as 2.5KV and angle of 6° is confirmed.

The $V_C$ being a direct measure of the SE coefficient, follows the same trend with respect to theta. The curve goes through a maximum when the beam is incident almost perpendicular to the surface i.e. at 0° angle. It follows a minimum at an angle equal to +90°. At angles close to theta = 0°, (i.e. perpendicular to sphere), the generation of SE takes place just near the surface so that the probability of the SE to come out of the surface increases. As the angle of incidence goes towards +90°, the penetration of primary electrons and thereby creation of SE takes place at farther depths, decreasing their migration probability.

3.7 OBSERVATION OF LEAKAGES USING VC

A qualitative estimation of leakages around the conductors carrying the bias voltages can be found in Fig.3.12. Fig.3.12a shows two conductor terminators spaced by about 0.4 mm at their closest approach. The terminator 1 is permanently ground. Terminator 2 is given changing bias. After application of negative bias (-8V), distinct intensity changes are observed in the region between the two conductors 1 and 2 as can be seen in Fig.3.12b. This can be probably correlated to voltage
Fig. 3.12: Voltage contrast indicating leakage around a conductor in a thick film hybrid circuit
(a) SE image without bias
(b) SE image at -8V bias (VC image)
distribution in the media between the terminators caused by leakage currents \cite{78,79}.

Although the voltage bias in a passive circuit is not restricted during experiments, the leakage observed at -8V bias indicates that one should not go for higher negative biases.

3.8 SELECTION OF PARAMETERS

After doing these experiments on VC with a flat specimen and an angular specimen, parameters for further experiments on testing of ICs are fixed as follows: Accelerating voltage = 2.5KV, voltage bias of 6V maximum for ICs, and angle of 6° or i.e. almost 0°, implying zero tilt to the specimen.

In the next chapter, the initial steps of algorithm development before setting up with processing of acquired images are discussed.