SIMULATION OF IMAGES AND THEIR PROCESSING
4.0 INTRODUCTION

After setting up the parameters for studying the VC images of ICs, some initial study of image processing techniques possibly required for SEM image processing is undertaken. For this purpose a 'simulation of image' approach is chosen. Before acquiring actual images of ICs, a simulated image of a conductor pattern is selected for processing. In this image, for topography with two grey levels, presence of pattern is given one intensity level and absence of pattern (background) is chosen as another intensity level. Random noise is incorporated in the simulated image. SNR improvement is obtained using histogram modification by windowing method. A method of VC isolation in intensity domain is developed. The algorithms present the implementation of image information improvement concepts. They can be applied with proper domain considerations to spatial domain images as well.

While simulating the conductor pattern SEM image, no consideration of material type is done. Only conductor and background are chosen for two intensities as explained above.

The simulation and processing of the selected image is carried out along the following steps.
1. Simulate topography pattern (two grey levels).
2. Simulate random noise in the pattern with various SNR conditions.
3. Histogram modification to reduce noise.
4. Restore pattern.
5. Simulate VC pattern (four grey levels).
6. Simulate random noise in VC pattern.
7. Difference of VC pattern and topography pattern.
8. Processing for improvement of difference image.
9. Isolated VC pattern
10. Comments on observed faults

All these processes will be explained in details in the following articles.

4.1 SIMULATION OF TOPOGRAPHY

Simulation of a conductor pattern SEM image is done on the VAX-11/730 computer. The image array is taken as a 64x64 matrix of Hex (H) numbers. Many combinations of Hex numbers for representing two grey levels (intensities) are tried. The concept of two grey level image simulation can be explained with the help of a square wave signal shown in Fig.4.1. Here the lower level indicated by I1 is lower intensity signal in the image representing topography. The high intensity background noise is indicated in Fig.4.1 by I2, the higher step. A representative simulated pattern is given in Fig.4.2a, with high intensity (I2='B'H), as background and lower intensity (I1='4'H) as the topography signal constituting the conductor image. Fig.4.2b is the histogram of the image shown in Fig.4.2a. The peaks at two intensity values namely 'B'H and '4'H can be clearly seen in Fig.4.2b.

4.2 SIMULATION OF VC

Considering the fact that secondary electron (SE) emission increases when the specimen is negatively biased and decreases when a positive bias is applied\(^2^7\), simulation of VC is done. In the previous case only presence or absence of the pattern is to
Fig. 4.1: Signal waveform for noise-free topography image (Two grey levels)
Fig. 4.2 (a): Simulation of topography image for a conductor pattern
Fig. 4.2 (b): Histogram of simulated conductor pattern image.
be depicted. Therefore only two intensity levels are chosen. But for VC simulation, to indicate difference in intensity due to applied bias, two more intensities are required. This can be represented by three steps signal as seen in Fig.4.3.

Fig.4.4a, represents the condition in Fig.4.3. The conductor pattern is biased. Pad '1' is given 0 volts and pad '3' is biased with negative voltage. It is assumed that there is a fracture in conductor line connecting pads '1' and '3'. The simulated fracture can be marked by different intensities indicated by '8'H and 'A'H ; 'A'H being the higher intensity and '8'H the lower. Other patterns are kept at same intensity for simplicity in further processing.

Fig.4.4a and b show image and the histogram of the four grey level simulated image representing the signal. The image in Fig.4.4a shows the negatively biased conductor appearing more bright. It is indicated by intensity 'A'H. The common line, marked by no.1 in Fig., being directly connected to the conductor should show same intensity. But due to the simulated fracture in Fig.4.4a, it is allotted the intensity '8'H. Fig.4.4b shows the peaks at intensities I2 ('B'H), I1 ('4'H), I4 ('8'H), I3('A'H) respectively.

The above two patterns of simulated images formed the basis of our images for developing different image processing programs. The method adopted for simulation is as follows : The conductor pattern decided for simulation is first drawn on a graph paper, keeping in mind that each square (0.01cmx0.01cm) on it correspond to one pixel of the image. Thus a binary image of the type pixel/no pixel is formed. This pixel array is 64x64.
Fig. 4.3: Signal waveform for noise free topography image (Four grey levels)
Fig. 4.4 (a): Simulation of voltage contrast image of conductor pattern.
Fig. 4.4 (b): Histogram of simulated voltage contrast image of conductor pattern.
To simulate this image as data for image processing, a FORTRAN-77 program is written. This program initialises a 64x64 matrix with a constant intensity initially. Then interactively, it asks for the intensity values (within range 0-15 or 0-'F'H) to be allotted to background and pattern intensity. In case of VC simulation the program asks for four intensities in all. These correspond to the intensity changes taking place in the VC image after application of bias.

The topography simulation program then generates the data array in memory according to the drawing on the graph paper. It fills all the array with background intensity ('B'H) initially. It then replaces the intensity 'B'H by '4'H at the required pixels for indicating presence of pattern (topography) in the array. Thus the 64x64 array is completely filled by two intensity values.

In VC simulation, only the biased part changes intensity from background and topography values. So these intensities are replaced by appropriate, lower ('B'H) due to fracture, or higher ('A'H) due to negative bias, values of intensities. Thus the resulting image has four intensity values in all.

A question may arise about the choice of the spatial as well as intensity resolution of the simulated image. We have chosen a value of 64x64 because this is a moderate spatial resolution in terms of processing speed. Another point considered is the output medium. Since the character printer attached to VAX-11/730 is decided as a device for hardcopy printout, the suitable image file size is 64x64, so that a displayable image is
generated on a 132 column stationary. The intensity resolution is chosen so as to suit the character printer. Since it is to be a two dimensional printout, only values 0-'F'H could be displayed and the intensity resolution is fixed as four bits only.

4.3 INTRODUCTION OF NOISE IN SIMULATED IMAGES

Noise is always associated with the SEM image. It is usually caused by the random noise in video amplifier. To make the simulated images realistic, noise is also introduced in them. A random noise generation program is written to simulate noise in the topography as well as VC images. Use is made of Random number generator function, built in the VAX-11 FORTRAN 77. This function is used to introduce noise with various amplitudes ranging from -4 to -1 and +1 to +4.

To compute the random noise, a program is written in FORTRAN 77 on VAX-11/730. This program asks for the random number seed (KSEED) and noise amplitude (IAMP) interactively. Then there are two flags generated using this KSEED, (i) RVAL = RAN (KSEED) and (ii) SIGN = RAN (KSEED). If the flag, SIGN > 0.5 then the noise amplitude (IAMP) is made negative (-IAMP), otherwise it is positive (+IAMP). The superposition of this noise amplitude on the array (ITF) value at a position I,J i.e. ITF (I,J) is done. After superposition the resulting signal amplitude (RNB) becomes,

\[ RNB = ITF (I,J) + IAMP \times RVAL \]

For computing the output image, only the integral part of the signal is considered using the nearest integer (NINT) function in FORTRAN 77. The value is then stored in the ITF array at the same position as follows,
ITF(I,J) = NINT (RNB)

Then again some correction in the array pixel values is made to cut the negative spikes, i.e. values less than 0 and the positive spikes, i.e. values greater than 'F'H. For negative spikes a constant value of 0 is given. Similarly for positive spikes, a value of 'F'H is chosen.

This program finally computes the SNR in the resulting image from the input intensity amplitudes (I1, I2) and the IAMP the amplitude of the noise using the relation,

$$\text{SNR} = \frac{(I2-I1)}{\text{ABS}(\text{IAMP})} \times 2$$

Fig.4.5 shows five different Signal to Noise Ratio (SNR) considerations obtainable with the developed program. The first condition (Fig.4.5a) has a background intensity of 'E'H and topography intensity of 'l'H. The sinusoidal signal represents the superposed noise of different amplitudes. The (SNR)_M is the minimum Signal to Noise Ratio (i.e. maximum noise) obtainable with this combination of intensities. The (SNR)_M is defined as the absolute difference between the original two intensities, divided by the maximum noise amplitude permissible with the chosen intensity components. Thus in the first case with I1='l'H and I2='E'H and if the noise amplitude exceeds +1, the level I2 with noise will exceed 'F'H, and to keep the signal within 0-'F'H level clipping will be required to be done. This may not result in a true representation of the noisy image. Therefore the minimum SNR in this case will be 6.5. With '2'H and 'D'H as the intensities (Fig.4.5b), the (SNR)_M comes out to be 2.75. The minimum possible SNR's for other combinations are given in Fig.4.5. For simulation (SNR)_M of 0.875 is selected, wherein
Fig. 4.5: Different signal to noise ratio (SNR) conditions with simulated image.
intensities I1 and I2 are represented by, I1='4'H and I2='B'H for further processing. The simulation of these intensities is already discussed with reference to Fig.4.2.

The worst case of obtaining an image is with SNR < 1, i.e. the image in which information is buried deep in noise of higher amplitude. Fig.4.6a shows simulated noisy image of the pattern discussed before (Fig.4.2a), with SNR = 0.875. Random noise is generated using KSEED = 334411. Fig.4.6b gives the histogram of the noisy image. Comparison of Fig.4.6a with Fig.4.2a assures the loss of information in the image. To restore this image (Fig.4.6a) from noise and to obtain original image (like Fig.4.2a), is a difficult task. Therefore the noise improvement technique is developed which is tried on the images with SNR < 1, in topography images and voltage contrast images to demonstrate the capability of the technique.

Fig.4.7a and b give the simulated noisy voltage contrast image and its histogram respectively. As can be seen the voltage contrast features are completely buried in noise. Fig.4.7a the VC noisy image, appears to have no correlation with the original VC image of Fig.4.4a. Detecting any useful information from this image (Fig.4.7a) is rather difficult. This image is chosen for demonstration of voltage contrast image isolation algorithm.

4.4 HISTOGRAM REPRESENTATION OF NOISY IMAGES

An image can be segmented with respect to various intensity levels. Histogram is a representation of this segmentation. It indicates the image distribution as a function of intensity levels. As discussed in article 4.1, the background is of higher
Fig. 4.6 (b) : Histogram of noisy image (SNR < 1) of the simulated circuit.
Fig. 4.7 (a): SNR < 1, voltage contrast image of simulated circuit.
Fig. 4.7 (b): Histogram of voltage contrast image (SNR < 1) of simulated circuit.

KSEED = 1133225
SNR = 0.875
intensity than pattern (object) intensity of the image. Ideally the background and pattern intensities form two distinct peaks in a histogram which are far apart. In this case extraction of the object from the background is simple. The peak in the histogram at largest intensity corresponds to the background region and the successive peaks at lower intensities correspond to various parts of the object. Fig.4.2b is the histogram of noise free topography simulated image in Fig.4.2a. The intensities ('4H' and 'B'H) form the segment boundaries. Similarly Fig.4.4b is the histogram of noise free VC simulated image, in Fig.4.4a, with intensities '4'H, '8'H, 'A'H and 'B'H as segment boundaries. Now it is possible to select various parts of the object just by selecting the appropriate segment intensities and choosing only those pixels having this intensity as belonging to the part of the object.

In practical situation for noisy image, there is always a distribution of intensities in both the background and the object regions of the image. The peaks corresponding to the background and parts of the object can be assumed to be gaussian function with standard deviations (Fig.4.8a) $\sigma_o$ around the intensity I1 corresponding to object intensity and $\sigma_b$ around the background. If the standard deviation increases, the histogram may have overlapping peaks as shown in Fig.4.8b.

In extremely noisy situations (e.g. SNR < 1) the signal and noise intensities get mixed in such a manner that no distinction can be made in the noisy image. The histogram contains lot many peaks and it is difficult to isolate the object from the
Fig. 4.8: Histograms showing

(a) separate gaussians

(b) overlapped gaussians
background at discrete intensity segments. This case is shown in
in Fig.4.6b, which represents histogram of noisy topography
image with KSEED = 334411 and SNR = 0.875. Since it is not
possible to distinguish between the background and object
intensities, the standard deviations are indicated by $\sigma_0^1$, $\sigma_0^2$, etc. i.e. corresponding to object only. The values of the
standard deviations are found to be closely related to the noise
amplitudes in the signal.

Histogram in Fig.4.7b represents the distribution of
intensities for noisy VC simulated image of the conductor
pattern. This being a case of SNR < 1 (KSEED = 1133225), many
peaks can be seen similar to Fig.4.7b. In topography simulated
image, noise is simulated around two intensities '4'H and 'B'H.
For VC, noise is generated with reference to four intensities :
'4'H, '8'H, 'A'H and 'B'H. Therefore the resulting histogram in
Fig.4.7b shows many overlapping gaussians with standard
deviations $\sigma_0^1$, $\sigma_0^2$, ... etc.

The VC noise simulation can be done in two types, viz.,
correlated and uncorrelated. In a correlated noise case, the
noisy topography image and VC image are generated using same
KSEED value, i.e. same random numbers. This results in similar
noise pixels corresponding to common intensities ('4'H and 'B'H),
in the two images. For uncorrelated noise, however, the KSEED
values for generation of random noise in simulated topography
images and in simulated VC images are different, thereby giving
rise to different noise pixels even for the common intensities
('4'H and 'B'H). These two cases with reference to VC isolation
will be discussed in article 4.6.
4.5 HISTOGRAM MODIFICATION METHODS FOR REDUCTION OF NOISE

Image enhancement by histogram modification is described in the literature\textsuperscript{68,85,46}. This has been discussed earlier in article 1.5.4.1. A new smoothening algorithm to reduce noise in the simulated noisy topography image (like in Fig.4.6) of the conductor pattern, is developed. This algorithm will be explained in this section.

4.5.1 Peak searching methods

The methods tried are the following:

Initially a method based on the first differential is chosen. In this, a differentiated array of the histogram of the noisy topography image is found. This array should show a maximum at the peak value of the noisy histogram. However, this histogram consists of lot many peaks and the restoration of the image using first differential method is not possible.

Then a method based on the second differential is tried. It is well known that the second differential is 0 when there is a point of inflexion in the array. Therefore for a maximum intensity value, an intensity value is chosen from the histogram for which second differential is 0 and first differential is negative. This method also failed because of two-three successive peaks in the histogram of the noisy image.

The third method is based on absolute difference of histogram values, and applying windowing technique for reconstructing the image.

To start with the difference of the number of pixels at any intensity value and number of pixels at '0' intensity is found
and stored in an array. The reason for this choice of '0' intensity as reference is because while simulating the image, clipping of noisy image at '0'H and 'F'H is done for negative and greater than 'F'H intensity values. In effect it is possible that number of pixels with intensity '0'H or 'F'H may go high (maximum). But this is not the actual peak and hence the peaks at intensities near '0'H or 'F'H are not considered as peaks.

Fig.4.6a shows the noisy image with SNR=0.875 and the random number seed chosen to be 334411. The value of the histogram array for first intensity ('0'H), in this case is 145. The histogram is therefore translated by 145.

Fig.4.9a shows the noisy image with KSEED = 445511 and SNR =1.16667. The noise amplitude in this case is + 3. The histogram of this image is shown in Fig.4.9b. This histogram is also translated but since the value of the histogram array corresponding to intensity '0' is 0 in this case, the translation of the histogram array by this value has no effect on the histogram.

The peaks in the histogram are found based on the following criterion. There is a change of slope of histogram curve at the intensities Ip-\text{d}Ip and Ip+\text{d}Ip where \text{d}Ip is the intensity step and Ip is the peak intensity. The histogram without noise showed two peaks, as mentioned in article 4.4. Since the object is in lighter intensity pixels, the extreme peak is neglected as background. The object is reconstructed by selecting all the pixels having the peak intensity (Ip).

In Fig.4.6b, there are peaks at intensities '1'H, '5'H,
Fig. 4.9 (a) : SNR > $\frac{1}{2}$ , noisy image of the simulated circuit.
Fig. 4.9 (b): Histogram of noisy image (SNR > 1) of the simulated circuit.
'7'H, 'B'H, and 'D'H respectively. Amplitude of noise is ±4.
Considering this noise amplitude and since the object and
background being at '4'H and 'B'H, there are more number of
pixels around '7'H ('4'H + '4'H = '8'H and 'B'H - '4'H = '7'H).
Hence only one peak is expected in the histogram which is
observed in Fig.4.6b at '7'H. At intensity '7'H the peak is
highest. Pixels with value '7'H only are considered for
restoration. Rest of the pixels are given intensity 'B'H.

The peak searching algorithm is also applied to Fig.4.9a,
with SNR > 1. Fig.4.9b shows the histogram of noisy image of
Fig.4.9a. As can be seen there are two peaks, one at intensity
level '5'H and the other at intensity 'D'H. The peak at 'D'H is
nearer to the expected background peak at 'B'H and peak at '5'H
is nearer to the expected ('4'H) peak of pattern. Hence every
background pixel is kept at 'B'H and image pixel at '5'H.

4.5.2 Windowing

Instead of segmenting at a single value of intensity (Ip)
corresponding to the histogram peak, a window of varying width
(w) is defined around the peak in the histogram. It is then
possible to isolate pixels corresponding to objects and
background with reference to the peak intensity (Ip). Optimum
window widths around every gaussian peak are of the order of the
standard deviations. In the program for windowing, a window input
is read from the keyboard. This is used to select the pixels
belonging to the simulated conductor pattern. If the modulus of
difference of the pixel intensity and the peak intensity (Ip) is
less than or equal to the window width, then the pixel is
considered to belong to pattern, otherwise the pixel is given a constant value of intensity (corresponding to background), to indicate that it belongs to the background in the image.

For the case of SNR < 1, the different windows chosen for restoration of patterns as explained above are 1, 2, 3 and 4. It is expected that the window corresponding to the maximum noise amplitude (+4), restores the image best. The chosen window = 4 implies that pixel with intensities from '3'\text{H} to 'A' \text{H} will be selected as pattern pixels and the other pixels will be replaced by value 'B'\text{H}. This case with window = 4 can be seen in Fig.4.10a. The pattern is not restored till window = 4.

The histogram of the restored image in Fig.4.10b shows two peaks at '7'\text{H} and 'B'\text{H} intensity values. The nature of the histogram is similar to the histogram of original noise free image as in Fig.4.2b.

But even if there is good quantitative recovery as can be predicted from these facts, the resulting image (Fig.4.10a), does not have any pattern information. The restored pattern does not resemble the original image (Fig.4.2a) any more.

To test the performance of the windowing algorithm for the case SNR > 1, various window values are given. In the first place (Fig.4.11a), window = 1 is tried. Therefore all the pixels with value 4 to 6 are replaced by peak value = 5 and the rest of image is given value 'B'\text{H}. The resulting image has 1138 pixels contributing to information. The histogram in Fig. 4.11b shows two peaks marked by x, at intensities '5'\text{H} and 'B'\text{H}. The image (Fig.4.11a) is not much clear, and hence one can go for another window = 2.
<table>
<thead>
<tr>
<th>$\xi$</th>
<th>0</th>
<th>3</th>
<th>35</th>
<th>25</th>
<th>12</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>0</th>
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<th>0</th>
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<tr>
<td>$\eta$</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 4.10 (a) : SNR $\ll 1$, image obtained at window width = 4.
Fig. 4.10 (b): Histogram of image (SNR < 1) of the simulated circuit at window width = 4.
Fig. 4.11 (a): SNR > 1, image obtained with window width = 1
Fig. 4.11 (b): Histogram of image (SNR $> 1$) obtained with various window widths and after median filtering.
In Fig. 4.12, the image recovery with window = 2 can be seen. The increase and decrease in amplitudes of the peak at intensities '5'H and 'B'H respectively can be seen in Fig. 4.12 marked by a circle. Still the pattern is not recovered up to the expectation. Therefore window = 3 is tried.

Here as per expectation of the correlation of the noise amplitude (+3) and the window width, the pattern starts appearing clear (Fig. 4.13). Again there, a quantitative increase in amplitude at intensity '5'H and decrease in amplitudes at intensity 'B'H in the histogram in Fig. 4.11b marked by a triangle.

4.5.3 Median Filtering

After application of windowing procedure, next problem encountered in the enhancement of simulated images, is removal of noise of the type of impulses or sharp discontinuities in the signal. This noise indicates the presence of high frequency components in the signal. Removal of this type of noise is not possible with linear filters. In such situations nonlinear type of filtering like median filtering is necessary\textsuperscript{68,86,85}.

The median (MED) of window N (N is odd), for a one dimensional array of pixels P(I) is defined as the intensity value, such that there are (N-1)/2 or (N+1)/2 pixels in the array with intensity less than or equal to the defined intensity. This definition of a median can be extended to two dimensional images as well. We have chosen a one dimensional median of window = 3 for removal of impulse type of noise in Fig. 4.13. It can be expressed mathematically for a one dimensional array P(I) as
Fig. 4.12: SNR $> 1$, image obtained with window width = 2
Fig. 4.13: SNR > 1, image obtained with window width = 3.
follows:

\[ P(I) = \text{MED}(P(I+J)) \]

where \( J = -1 \) to +1. This reduces many unwanted pixels in the image.

In Fig.4.13 few high intensity value pixels still appear in the pattern. After application of a one dimensional median filter to it, resulting image (Fig.4.14) shows improvement in the pattern to a larger extent and the pattern now resembles the original. This is indicated quantitatively by stars in the histogram in Fig.4.11b as the topmost value corresponding to the intensity '5'H and lowermost value corresponding to intensity 'B'H.

4.5.4 Measurement of object recovery with processing

A parameter defining the percentage of object coverage for every processing step is defined as

\[ P_C = \left( \frac{P_O}{P_t} \right) \times 100 \]

where \( P_O \) is the number of pixels of object and \( P_t \) is the total number of pixels per frame, e.g. in case of simulated image \( P_t = 64 \times 64 = 4096 \). The factor \( P_C \) is used to evaluate the effect of processing step on the degree of image restoration.

Computation of \( P_C \) for the case of SNR < 1, at window = 4 from Fig.4.10a is 62.5. The original image (Fig.4.2a) has \( P_C = 55.224 \). Thus the processed image has quantitatively restored the noisy image.

The \( P_C \) is also computed for processing of the noisy image in Fig.4.9a. Table 4.1 shows the percentage of the pattern coverage.
Fig. 4.14: SNR > 1, image obtained after median filtering to the image with window width = 3.
Table 4.1

Variation of $P_C$ with processing steps for $SNR > 1$

<table>
<thead>
<tr>
<th>No.</th>
<th>Processing step</th>
<th>$P_o$</th>
<th>$P_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>-</td>
<td>2262</td>
<td>55.224</td>
</tr>
<tr>
<td>2.</td>
<td>Window = 1</td>
<td>1138</td>
<td>27.778</td>
</tr>
<tr>
<td>3.</td>
<td>Window = 2</td>
<td>1696</td>
<td>41.406</td>
</tr>
<tr>
<td>4.</td>
<td>Window = 3</td>
<td>2218</td>
<td>54.150</td>
</tr>
<tr>
<td>5.</td>
<td>Median Filter</td>
<td>2241</td>
<td>54.7119</td>
</tr>
</tbody>
</table>
(P_c) at different stages of the algorithm for the case of SNR > 1.

The increase in P_c with increase in the window width can be seen quantitatively from Table 4.1. The last processing step i.e. the median filter results in a P_c(54.7119), nearer to the P_c for the original image (55.224). This emphasizes the utility of the developed technique quantitatively.

4.5.5 Discussion on the results of noise reduction algorithm

It can be seen from the results in article 4.5.2 and 4.5.4 that there is a quantitative enhancement in the image for SNR<1. However mere quantitative enhancement is not effective in restoration of the image, it should be accompanied by the qualitative improvement as well. Therefore it can be concluded that the algorithm fails for case of SNR < 1. This does not hamper the reliability of the algorithm, since SNR < 1 is not an image neither a practical situatuion. It is only noise.

The qualitative and quantitative improvement in the image with SNR > 1 after processing implies, that the algorithm can be applied to such images with good results.

4.6 VOLTAGE CONTRAST ISOLATION IN SIMULATED IMAGES

Isolation of voltage contrast from the topography and material contrast, inherently present in the SEM images, is a difficult task. Isolation is necessary to obtain a pure voltage relationship with respect to applied bias, of the IC under study.

Oatley has developed a hardware method for isolation of VC, carried out first in 1969. He has used a p-n junction diode to
study forward and reverse biasing effects on it. The signal from the collector, in VC mode, is separated into two channels by two gates A and B. The signal coming from gate A constitutes the VC signal and that from gate B is zero bias signal. After passing through separate detectors, the differentiation of the two signals (from gates A and B), is carried out which under ideal conditions gives the pure VC.

Gopinath and Sanger\textsuperscript{89} have reported a simple method of isolating VC using a phase sensitive detector. In their method, the beam is not chopped but the device bias is pulsed at say 10KHz. The video output therefore contained topography only during the bias-off period and topography plus VC during the bias-on period. Their difference at 10KHz constituted the 'VC only' signal. The output of PSD is regarded as the averaged product of signal and reference and therefore a function of their phase difference and the signal amplitude. When the phases of the reference and signal are coincident, the output is detected VC only signal, with the phase variation taken into account.

The above two methods are developed using different hardware development techniques. These days the trend is towards development of various software techniques for implementation of the same purpose. Use of digital image processing techniques for isolation of VC in testing ICs has been carried out recently by Fujioka et al\textsuperscript{43} in 1982. They prepared a set of SEM images of the IC under test at various biased and unbiased conditions and processed them to separate out VC. Other groups working on the software development based on image processing techniques for isolation of VC are Purukawa et al\textsuperscript{44} in 1986, and T.C. May et al\textsuperscript{4}
since 1982. These papers are already discussed in article 1.5.4.3.

During this work, we have developed an algorithm based on the image processing techniques to enhance and isolate VC in noisy simulated SEM images of a biased conductor pattern. Again the case of SNR < 1 is chosen for this purpose.

Fig.4.15a shows the topography simulated image with KSEED =1133225. The histogram array is given below the image and is plotted in Fig.4.15b. Fig.4.7a and b are the VC simulated image and histogram of the same conductor pattern (discussed in article 4.4), with same random number seed (1133225) respectively. In this pair of topography and VC images, the random number seeds are same. This forms the correlated noise situation discussed in article 4.3.

Fig.4.16a and b show the simulation of noise in the VC image with seed =331. Fig.4.17a and b show the noisy simulated topography image and histogram of the conductor pattern with different seed = 113. The SNR is same (0.875) for both these images. This generated uncorrelated noise in the two images as discussed in article 4.3.

4.6.1 Three point averaging followed by subtraction of images

Initially the noisy topography and VC images are smoothened for betterment using the three point averaging technique. In the three point averaging procedure, the averaging of the \((I,J)^{th}\) pixel value is done with respect to \((I-1,J-1)^{th}\) and \((I+1,J+1)^{th}\) pixel values. The median filter chosen for SNR improvement is not chosen here because of absence of impulse type of noise in the
Fig. 4.15(a): SNR < 1, topography image with random number seed = 1133225
Fig. 4.15(b): Histogram of image (SNR < 1) with random number seed = 1133225

KSEED = 1133225
SNR = 0.875
\[ \text{.4.16 (a): SNR} < 1, \text{ voltage contrast image with random number seed = 331} \]
Fig. 4.16 (b): Histogram of image (SNR < 1) with random number seed = 331
Fig. 4.17 (c): SNR << 1, topography image with random number seed = 113
KSEED = 113
SNR = 0.875

Fig. 4.17 (b): Histogram of image (SNR < 1) with random number seed = 113
difference image. The image array is 64x64. Therefore choice of a neighbourhood of 3 is appropriate. Any other higher degree averager like 5 point or 7 point might hamper the details in the noisy image. After the averaging procedure, the pixel by pixel difference of the two images is computed and the pattern is stored in an array.

For the pair of images with same seed (correlated noise), after three point averaging, simple pixel to pixel subtraction procedure is applied to Fig.4.7a and 4.15a. Fig.4.18a is the difference image and Fig.4.18b is its histogram. The peak in Fig.4.18b at intensity '0'H indicates that the subtraction of the two images (Fig.4.7a and 4.15a) has cancelled the correlated noise in the two images. This has resulted in many pixels with intensity '0'H. In Fig.4.18a, apart from few low intensity pixels in the fractured conductor pattern of the image, the algorithm has separated the biased part very clearly.

The same method of three point averaging followed by pixel to pixel subtraction of VC and SE images is used for VC isolation in uncorrelated noise case. As shown in Fig.4.19a and b, difference histogram and image are obtained by subtraction of three point moving averaged images of Fig.4.16a and 4.17a, does not give any relevant information regarding the VC in the simulated images. The obtained limited image improvement is due to the cancellation of correlated noise in the images. By following the averaging followed by differentiation method, whatever noise has remained is due to the uncorrelated seeds.

Further improvement in difference image is tried again by
Fig. 4.18 (b): Histogram of difference image of topography and voltage contrast images with same random number seed (1133225)
Fig. 4. (a): Difference image of topography and voltage contrast images with different random number seeds (113 and 331, respectively)
Fig. 4.19 (b): Histogram of difference image of topography and voltage contrast images with different random number seeds (113 and 331 respectively).
smoothing process like three point averaging. Fig. 4.20 shows
the smoothened difference image obtained after three point
averaging procedure applied to Fig.4.19a. In Fig.4.19b, the
histogram obtained after smoothening of difference image is
indicated by dashed lines. This shows a higher peak as compared
to the histogram of Fig.4.19b indicated by continuous line. Thus
there is an improvement in image.

However, even after this procedure, the few pixels, not
contributing to information are retained in the image. To remove
these pixels, an epsilon procedure is tried out.

4.6.2 The epsilon procedure

This algorithm is based on the 8-connectivity property of
the pixels. It is known that in a two dimensional array of
pixels NP, each \((I,J)\)th pixel has eight neighbours in eight
directions. The intensity of the pixel at \((I,J)\) is related to the
intensities of these eight neighbours. An algorithm is developed
to check if the intensity at \((I,J)\) is much different from the
average intensity of its neighbours or not. This method will help
us in isolating or smoothing out the high intensity scattered
points in the background or in the pattern of interest.

The algorithm initially adds the pixel values of all the
eight neighbours and the pixel of interest. Then it averages this
sum by dividing by 9. Next, it checks if this average intensity
is less than some value epsilon. The value epsilon is based on
the prior information of intensities corresponding to background
and object. If the pixel is within object, then the average of
eight connectivity neighbours corresponds to intensity of the
Fig. 4.20: Smoothing of the difference image shown in 4.19 (c). (Histogram of the same is shown in 4.19 (b).)
object. Otherwise, it contributes to the background. If so, then it makes the intensity of pixel of interest equal to zero. Otherwise the original value of intensity is retained. This can be explained mathematically as,

$$\text{SUM} = \frac{\text{NP}(I+K, J+L)}{9},$$

for $I$ and $J = -1$ to $+1$. If $(\text{SUM}) < \text{EPS}$ then $\text{NP}(I, J) = 0$, otherwise, $\text{NP}(I, J)$ is unchanged.

Thus the resulting effect is preservation of the intensities if the pixel belongs to the image pattern array. On the other hand, if the pixel is a noise spike in background, then it is smoothened by replacement of this intensity by zero.

Application of this algorithm to Fig.4.20 has resulted in Fig.4.21a. This is a much better image. The qualitative improvement can be clearly seen. Isolated pixels in Fig.4.20 are almost absent in this image. The histogram in Fig.4.19b indicates the quantitative improvement (continuous line). The peak at intensity '1'H in Fig.4.19b is now shifted to intensity '0'H after epsilon procedure. The number of pixels at intensities corresponding to isolated pixels in the image is also seen to be reduced in Fig.4.21a.

This image although resembles the pattern of single isolated conductor with a fracture, the background intensity is too low, i.e. '0'H. In the simulated image (Fig.4.2a), the background intensity is chosen to be 'B'H. Thus the background is to be restored. The pattern pixels in the simulated VC image had two grey levels. Therefore the restored pattern should also have 2 grey levels. To make these corrections in the final image, the peak searching procedure described in article 4.5.1 is used.
Fig. 4.21 (a): Epsilon procedure applied to the smoothened difference image shown in 4.20.
Fig. 4.21 (b): Histogram of epsilon procedure applied to the smoothened difference image shown in 4.20.
The peak search procedure applied to the image in Fig.4.21 has resulted in Fig.4.22

4.6.3 Discussion on VC isolation in noisy images

In the particular case of correlated noise, same random number seed is used for simulation of topography and the VC. Therefore after subtraction, correlated noise is cancelled out. Thus VC isolation is simple if the noise in VC image and topography image is correlated.

For the uncorrelated noise case, the output pattern is as per expectation. The isolated biased conductor can be seen clearly, indicated by intensity '3'H. To make the pattern distinct, the background as original image is given intensity 'B'H. The quantitative improvement in the image can be easily marked by comparison of histograms corresponding to Fig.4.21a shown in Fig.4.21b by continuous line and that corresponding to Fig.4.22 shown in Fig.4.21b by dashed lines. Thus it is possible to isolate VC in case of images with uncorrelated noise and with SNR as small as 0.875. But distinction between the intensities corresponding to regions below and above the microfracture is less in the uncorrelated noisy case as can be seen from Fig.4.21a.

4.7 CONCLUSION

In this chapter, we have described the method of simulation of VC and SE SEM images as raw data for development of image processing algorithms. To make these images realistic, a novel method of random noise generation is developed.
Fig. 4.22: Peak search procedure applied to the epsilon processed image shown in 4.21 (a). (Histogram of the same is shown in 4.21(b))
Development of a new algorithm for reduction of noise in the above image is done for extremely noisy situations with SNR < 1 and slightly greater than 1. The algorithm proves its utility for a case with SNR slightly greater than 1. The algorithm when proves to be good for such low SNRs, will surely be beneficial to the practically acquired SEM images for which SNR > 1.

Use of image processing is done for VC isolation in a simulated conductor pattern image. This technique is proved to be of use in this particular case with intensity resolution of 4 i.e. with 16 grey levels. However it can be easily extended for higher resolution.

To prove these algorithm to be potential, the same are applied to the practical images acquired from SEM and the results will be discussed in the sixth chapter.