A Line Extraction Method for Automated SEM Inspection of VLSI Resist

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Abstract—This correspondence presents a precision digital edge line detection method. It is developed for extracting edge contours of resist lines of submicron width as imaged by scanning electron microscopy. The accurate determination of resist edge lines is crucial for automatic measurement, microregistration and automatic detection of defects on resist lines.

Index Terms—Digital line detection, Hough transform, SEM imaging, VLSI resist, wafer inspection.

I. INTRODUCTION

Reliability control during integrated circuit fabrication is becoming more demanding as devices get smaller and denser. The fabrication of integrated circuits is a multistep process that includes developing photo resist patterns on wafers followed by etching, diffusion, oxidation, and implantation or metallization steps. Resist patterns used in device fabrication must have high integrity and conform to strict geometric specifications. Currently, wafers used in the manufacture of IC’s are electrically and visually inspected at various stages of fabrication, using optical microscopy, to ensure reliability of the circuits and to monitor the complex production process [1]–[6]. An optical-microscopy based automated reticle/mask inspection system has also become available [5]. Such inspection procedures and systems are feasible for patterns with linewidths greater than one micron. However, in-process inspection of submicron lines in VLSI (very large scale integration) wafers will require higher resolution than optical systems can deliver. Thus, scanning electron microscopy (SEM) and automatic image pattern analysis will be needed [7]–[11].

A SEM consists of an electron beam focusing and specimen scanning system with capability of synchronous specimen scanning, signal detection and display. Images obtained from a SEM are determined by the interaction of the scanning electron beam with the surface of the specimen and the stimulated emissions, either secondary emission or backscattered electron emission, received by the respective detectors. Contrast in a SEM image is normally due to specimen topology, chemical composition, as well as electric potentials. Relative to light microscopes the SEM has 10–100 times better resolution and 100–1000 times greater depth of field. Hence, it can resolve defects in submicron lines which cannot be resolved by light microscopes. Along with increased capabilities the SEM introduces new challenges for image processing because of the difficulties in contrast, noise, and edge properties relative to optical images.

In a VLSI resist pattern, straight line edges are the dominant features which are used for automatic measurement, microregistration and defect detection. Since the SEM imaging produces the blurring effect on edges of very fine resist lines, the accurate determination of resist edge lines is a critical problem. In this correspondence, we present a method for digital edge line extraction by a modification of the Hough transform.

II. A PRECISION DIGITAL EDGE LINE DETECTION ALGORITHM

Edge pixels in a field of view are first determined by an appropriate process. In our study, we considered SEM secondary emission images of resist on an aluminum film deposited on a silicon wafer. The incident electron beam causes some charging of the interior of the resist lines and blurring of the resist lines. We tried both Sobel gradient method and Laplacian-Gaussian method to determine edge pixels. Each field of view is digitized into 512 x 512 pixels of 256 gray levels. Sobel method gave either thick and noisy edges or broken edges, depending on the gradient old used. We chose to use the Laplacian–Gaussian operator which, under a proper choice of operator parameters, gave better results without shift in edge position. Fig. 1(a) illustrates a sample SEM image of resist lines. The spatial resolution of the digitization provides about 40 pixels per line width. Fig. 1(b) shows an experimental result of applying the Laplacian–Gaussian operator (with $w = 10$, where $w$ is the diameter of the positive central region of the operator) to a sample SEM image as shown. Fig. 1(c) shows the resulting zero crossing points on the resist line contours as well as on small contours in the noisy background and those inside the resist due to the charging effect. The subsequent task is to extract the resist edge contours, which contain relatively long straight line segments, and remove the other unwanted zero crossing points.

A. Modification of the Conventional Hough Transform Procedure

Straight lines may be detected by the Hough transform [12]–[14]. In practice, because of the noisy edge region and the nature of the digital lines, false lines and aberration lines were often obtained [15]. Although the standard Hough transform has been successfully used for some disk head inspection [16], we did not find it satisfactory for our application. There are two major shortcomings in the conventional procedure of applying the Hough transform for the detection of connected edge segments. First, it fails to check the edge pixel connectivity. Second, the count in an accumulator cell does not necessarily reflect the length of a line segment even if those edge pixels are connected.

Let the parameterization of a straight line in the (x, y)-plane be specified by its normal distance $\rho$ from the origin of the plane to the line and angular position $\theta$ of the normal; $\rho = x \cos \theta + y \sin \theta$. Each pixel $(x_i, y_i)$ is transformed into a sinusoidal curve in $(\rho, \theta)$-parameter plane. Let the $(\rho, \theta)$-plane be quantized into a quadruled grid, and the quantized region be considered as a two-dimensional accumulator array. The peak count $M$ in a $(\rho_i, \theta_j)$-cell indicates $M$ collinear pixels on a straight line in the image with its parameters $\rho_i$ and $\theta_j$. Let a $q \times q$ window be used for the transform and a count threshold $M_0$ be specified for detecting digital line segments with length equal to or greater than $M_0$, spatial units (containing at least $M_0$ connected and digitally collinear edge pixels) within the window, where a spatial unit is defined by the interpixel distance. Let $\theta$ be quantized by $\Delta \theta$, for example, $\Delta \theta = 9^\circ$, and $\rho$ be quantized in the same manner as $x$ and $y$. As illustrated in Fig. 2, the digital line A consisting of 19 connected pixels will be detected by the conventional Hough transform procedure if the count threshold is set at $M_0 = 11$. Here, the count at the accumulator cell $(18, 45^\circ)$ is 19, but this number does not reflect the actual length of the line which is 11 $\sqrt{2}$. On the other hand, an aberrant line B will also be detected because the 11 pixels marked by $x$, which are not completely connected, will give a count equal to the count.
threshold 11 at the accumulator cell (19, 36°). This is a false line consisting of three short line segments each of which has its length smaller than 11 units.

A new procedure has been developed to overcome these difficulties. First, it modifies the approach to increment the count in an accumulator cell by checking the content of an associated bit array of each cell, instead of increment unconditionally, such that the count indicates the actual length of the line segment if the pixels are all connected. Second, the threshold for the count in an accumulator cell is made adaptive to the orientation and location of the line segment under consideration (i.e., different threshold counts for different \((\rho_k, \theta)\)-cells). The procedure will be discussed in the following.

B. Construction of a Bit Array for Accumulator Cell

For each edge pixel \((x_i, y_i)\), compute the values of \(\rho_k = \rho(\theta_k)\) at different values of \(\theta_k = k \Delta \theta, \rho_k = x_i \cos \theta_k + y_i \sin \theta_k, \) where \(k\) varies from 0 to \((K - 1)\) and \(K = x/\Delta \theta\). When each \(\rho_k\) is rounded off, as designated by \(\hat{\rho_k}\), the ordered pairs, \(\{(\hat{\rho_k}, \theta_k)\}_{k = 0, 1, \cdots, K - 1}\), denote a set of accumulator cells for the edge pixel \(P_i = (x_i, y_i)\). The pair \((\hat{\rho_k}, \theta_k)\), however, defines a line \(L_{\hat{\rho_k}}\) within a one-unit wide band \((\Delta \rho = 1)\) centered at the digital line parametrized by \((\hat{\rho_k}, \theta_k)\), as shown in Fig. 3. In the following discussion, the digital line \((\hat{\rho_k}, \theta_k)\), is referred to as the connected pixels within the band.

Let the normal from the origin to the line \(L_{\hat{\rho_k}}\) intersects with \(L_{\hat{\rho_k}}\) at a point \((x', y')\), this point is termed the "normal intercept" of \(L_{\hat{\rho_k}}\). Compute the distance \(d_{\hat{\rho_k}}\) from the normal intercept \((x', y')\) to the edge pixel \((x_i, y_i)\), and round it off to an integer \(n\) to give a quantized \(d_{\hat{\rho_k}} = n\) of the distance along the digital line specified by the parameters \((\hat{\rho_k}, \theta_k)\). Let us construct a bit array for each accumulator cell; the array has a length of \((2q + 1)\) with an index running from \(-q\) through \(+q\). The index "0" corresponds to the location of \((x_i, y_i)\), that is, zero distance. Initially, all the bits in the bit array are set to 0. If \(x_i > x_r\), the bit corresponding to the
index "+n" is examined. If the bit is 1, nothing will be done. If the bit is 0, it will be set to 1 and the accumulator cell \((\rho_k, \theta_k)\) will be incremented by one. If \(x_j < x_l\), the negatively indexed "\(-\)" bit will be examined. If \(x_j = x_l\), then \(y_j\) in relation to \(y_l\) will be considered using either positively or negatively indexed bit.

If there are \(m\) consecutive "1"s in the bit array, it represents an edge line segment of \(m\) units in length on the digital line. That is, each bit in the array contributes to the corresponding edge line one unit of length at a location whose index value reflects the quantized distance from the normal intercept of the line \((\rho_k, \theta_k)\).

When a neighboring edge pixel \(P_j = (x_j, y_j)\) is considered (see Fig. 3), for the same \(\theta_j\), the line \(L_{ij}\) passing through \(P_j\) will be parallel to \(L_{kl}\). If \(\rho_k = \rho_l\), these two lines lie within the quantized band of the digital line parametrized by \((\rho_k, \theta_k)\). The distance \(d_{ik}\) is computed similarly from \(P_i\) to the normal intercept \((x_j, y_j)\). If \(d_{ik} = d_{ik} = n, P_k\) and \(P_j\) are considered at the same location as far as the digital line \((\rho_k, \theta_k)\) is concerned. Therefore, \(P_j\) should not increase the count in the neighboring accumulator cell \((\rho_k, \theta_k)\), otherwise, \(P_j\) and \(P_k\) would inappropriately contribute two units of length. Since the corresponding bit in the bit array has already been set by \(P_i\), that bit and the accumulator count will not be updated. In this way, the count in each accumulator cell will reflect the actual length of the digital line segment in the processing window if the pixels are all connected.

Each accumulator cell has two parts. One the first part is the count field for length measurement mentioned above. The second part contains the field for accumulation of the edge strength of pixels on the corresponding digital line segment (if the edge pixels are determined by the Laplacian-Gaussian edge operator, the edge line segment parameterized by \((x_j, y_j)\) is examined to determine the edge line segment \((x_j, y_j)\), the neighboring accumulator cells \((\rho_k + 1, \theta_k)\) and \((\rho_k - 1, \theta_k)\) are similarly incremented. Although the resulting counts in two neighboring accumulator cells in Fig. 4(b) are all greater than or equal to the specified threshold, the digital line \((\rho_k, \theta_k)\) is detected for its maximum count.

C. Assured Connectivity of Pixels Through Adaptation of Count Threshold

In this study, we used a 31 \(\times\) 31 processing window where the center pixel is referred to as the origin. It is intended to detect long digital line segments extended across the window. The number of connected pixels on each of these digital line segments and its length vary with its location and orientation. We consider those line segments in the window with length ranging from 29 up to 44.

With \(\Delta = 9\), \(\theta_j\) indexed from \(\theta_1\) to \(\theta_{36}\), and \(\rho_k\) indexed from \(-15\) to \(+15\), there are \(20 \times 31\) accumulator cells for the Hough transform. The full length of each of the corresponding 620 digital line segments can be computed, and the length threshold for detection of these line segments can be determined for individual accumulator cell. The length thresholds varying from 29 to 43 for longer digital line segments are entered into a table as shown in Table I, where the column and row positions of each entry are indexed by \(\rho_k\) and \(\theta_k\), respectively. Shorter line segments at other locations are not acceptable and their length thresholds are set at the highest level \("124"\): if any of them is a part of a longer line segment observable beyond the window, that segment will be detected when the window is moved 15 pixels to the right or downward. Thus the digital line segments of connected pixels, satisfying their individual length criteria, can be detected. For practical purposes, the adaptive threshold can be set at, say, 80 percent of the length values given in the table. It will allow at most 20 percent missing points in any detected line segment where pixel connectivity will be forced upon. The final counts in the accumulator array are examined against the adaptive threshold. Only those cells with counts equal to or greater than their respective thresholds retain their counts. Otherwise, counts will be ignored and reset to zero. In each processing window, the line detection process begins by scanning the accumulator array. Whenever a cell \((\rho_k, \theta_k)\) with satisfactory count is met, a search is made for the maximum count in a subset of 3 \(\times\) 3 cells with \((\rho_k, \theta_k)\) at its top left corner. A digital line segment parameterized by \(\rho_k\) and \(\theta_k\) is detected if the length count at cell \((\rho_k, \theta_k)\) is the maximum. If equal maximum counts occur at two cells in the subset, the two corresponding line segments are compared for their respective edge strengths and the one with stronger edge strength will be chosen. Many aberration lines can thus be eliminated.

D. Extraction of Resist Line Contours

It has been observed that higher contrast in brightness always exists across a resist contour in comparison to the contrast across edge contours introduced by the charging effect within the resist region. An average contrast measure across an edge line segment is computed as the arithmetic average of the unnormalized contrast across each edge pixel on the line segment. This contrast is defined as the difference in the maximum gray level and the minimum gray level over an interval of \(\pm5\) pixels orthogonal to the edge line. A threshold value for the average contrast is chosen based upon the learning samples. The digital line segments with stronger contrast measures are finally detected as the edge line segments of a resist pattern. The processing window is moved by 15 pixels to the right in succession, and then is shifted downward by 15 pixels to repeat the same process, so that there are 50 percent overlap of every pair of processing windows. The detected line segments are thus linked together to form longer straight line edges of the resist image. An experimental result is shown in Fig. 1(d). The curved portions are traced out in the edge map (zero-crossing edge image in this case), by starting from the end points of each straight line edge, to form a complete edge contour of a resist line. Small protruding and convoluted portions on the contour are due to defects on the resist line.

![Fig. 4. A further modification of count increment process for neighboring accumulator cells.](image-url)
detection process requires a large amount of computation and its processing time is a subject of serious concern. Toward this end, we have developed a systolic array processor architecture for this application. The microregistration can be performed by applying the unnormalized cross correlation of consecutive images acquired from a tilted position. Some of commonly observed defects: resist edge distortions (local swellings or local narrow-down of resist lines), bubbles or holes on resist lines, and strings (residual resist material) can be examined when the specimen is imaged in a tilted position. The determined edge lines in a test image can be used for measurement of resist line width and for microregistration of scanning electron images, for example, a 10-micron square, the line detection method is to be applied to locate processing blocks which are to be inspected or local narrow-down of resist lines, bubbles or holes on resist lines, and strings (residual resist material) on the sides of a resist line. The first two types are illustrated in Fig. 1(a); the third can be examined when the specimen is imaged in a tilted position. Some preliminary results on defect detection have been reported elsewhere [18]. With the very fine spatial resolution required for inspecting VLSI resist and with the practical constraints on data acquisition and image processing, one will have to sample only a few, say ten, positions on a wafer; this is also the practice being employed in the current semiautomatic VLSI metrology. Within a sampled field of view, for example, a 10-micron square, the line detection process requires a large amount of computation and its processing time is a subject of serious concern. Toward this end, we have developed a systolic array processor architecture for this line detection method so as to show its promise to be applicable for in-process inspection of VLSI resist.

IV. DISCUSSION

Our experiments have shown success of the above-described method of accurate detection of edge lines in SEM images of VLSI resist patterns. The determined edge lines in a test image can be used for measurement of resist line width and for microregistration with the corresponding lines of a golden image (a defect-free reference image) for defect detection. The microregistration can be performed by applying the unnormalized cross correlation of contrast methods [4] to locate processing blocks which are to be inspected by the defect detection algorithms. There are three types of commonly observed defects: resist edge distortions (local swellings or local narrow-down of resist lines), bubbles or holes on resist lines, and strings (residual resist material) on the sides of a resist line. The first two types are illustrated in Fig. 1(a); the third can be examined when the specimen is imaged in a tilted position. Some preliminary results on defect detection have been reported elsewhere [18]. With the very fine spatial resolution required for inspecting VLSI resist and with the practical constraints on data acquisition and image processing, one will have to sample only a few, say ten, positions on a wafer; this is also the practice being adopted in the current semiautomatic VLSI metrology. Within a sampled field of view, for example, a 10-micron square, the line detection process requires a large amount of computation and its processing time is a subject of serious concern. Toward this end, we have developed a systolic array processor architecture for this line detection method so as to show its promise to be applicable for in-process inspection of VLSI resist.

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