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An intelligent supervisory system for ion implantation in IC fabrication processes

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Abstract

This paper presents a real-time intelligent supervision system for IC ion implantation processes. A hardware interface is developed, to extract the features directly from the 2-D analog image signals of a beam map. A qualitative model for the beam scanning is then obtained, and the symptoms of abnormal operations can be analyzed to achieve on-line diagnosis. Furthermore, a fuzzy expert system is developed to advise operators on making appropriate adjustments for the beam scanning. This supervisory system has been implemented on Eaton NV-6200 A/AV ion implanters at the Taiwan Semiconductor Manufacturing Company. © *1999 Elsevier Science Ltd. All rights reserved.*

Keywords: Ion implantation; beam maps; supervision; feature extraction; symptom analysis; fuzzy expert systems

1. Introduction

The ion implantation is a crucial process in semiconductor manufacturing, for bombarding a material with energetic ions in order to embed the ions beneath the surface of the material. Doping of semiconductors with impurity atoms was originally done by diffusion of the dopant material into the substrate material. Diffusion is usually an inexpensive process, but it is typically slow, and must be performed at high temperatures. On the other hand, the use of ion beams (Rose, 1985; Myron and Zrudsky, 1987) provides several practical advantages over diffusion, and it allows the semiconductor engineers to conduct certain types of doping that cannot be performed with diffusion. To set up and monitor the beam scanning over wafers during implantation, a beam map display, which is directly related to the geometry of the beam scanning, is usually provided for the operators. To avoid unexpected situations or abnormal operations on the wafer, operators must monitor the beam map display continuously during the implantation processing. Nevertheless, economic losses due to the abnormal processing are still unavoidable because of human shortcomings. Therefore, the development of an automatic beam map supervision system on the ion implanter is desirable to avoid faulty implantation.

Fig. 1 shows a general supervision system, consisting of three basic modules: data acquisition, symptom generation, and decision making. The first stage of a supervision system obtains useful data from the systems concerned, from which the system behavior can be understood. Then, signals are processed through certain filters designed for monitoring. The second stage is the symptom-generation stage, which generates typical symptoms, significantly related to the operating conditions of the monitored systems, especially when the systems become abnormal. In addition, the definition of a relationship between the generated symptoms and the failures is required at the same stage. In the final stage, the decision-making mechanism judges whether the systems concerned are operating normally, according to the prior knowledge about the supervised systems. Moreover, the decision maker also has to advise the operators on taking appropriate actions to prevent further damage.

Image-processing techniques (Banks, 1990) are useful tools for recognizing visual patterns. In the 2-D beam map recognition, a direct method of achieving automatic monitoring is by using image-processing techniques.

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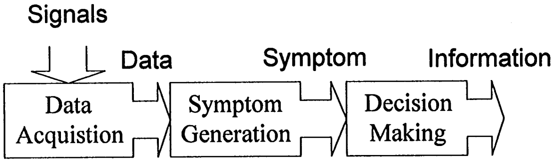

Fig. 1. Basic structure of a supervision system.

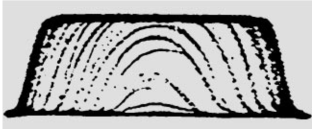

Fig. 2. A typical beam map display (Eaton Corp.).

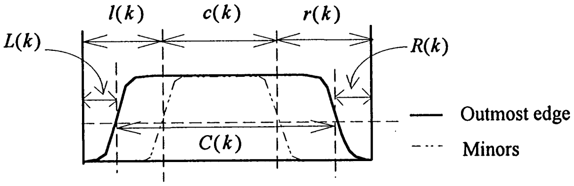

Fig. 3. The specification of a beam-map.

However, the image processing for pattern recognition is usually very time-consuming, so that real-time failure detection during implantation is almost impossible. On the other hand, high-performance image devices are expensive. Therefore, researchers and engineers have pursued alternative ways to perform real-time failure identification.

The goal of this paper is to develop a supervisory system that cannot only monitor the ion implantation process, but can also advise operators on the appropriate actions to maintain the operation in the event of a fault occurrence. A data-acquisition system using feature-extraction techniques is developed in this paper to simplify the 2-D beam map recognition into a 1-D feature analysis. Second, a symptom-generation system using qualitative models obtained from feature-failure analyses will be described. This system generates symptoms corresponding to uncentered beam positions on a wafer, as well as imbalanced beam-scanning amplitudes in the vertical and horizontal directions. In the final stage, since the ion beam setup of the implantation processes depends on engineers' experience and is fuzzy in nature, a promising approach for use in decision making is the use of fuzzy logic and expert systems (Negoita, 1985). A fuzzy inference engine will be used to overcome the linguistic uncertainties in the knowledge acquired from various experienced engineers. An expert system that stores knowledge in rules is further developed to provide advice for maintaining the operation within the specifications. In addition, the explanation facility provided by the developed supervision system can be further used for computer-aided operator training.

2. The beam map of the ion implantation process

The experimental system used here is the popular Eaton NV-6200 A/AV ion implanter, which provides a beam spatial resolution of 260 × 260 lines over a wafer (Dykstra, 1987). Fig. 2 illustrates an example of the beam map that is produced by overlapping the measured beam current over a wafer on the beam monitor (Eaton Corporation, 1992). The operating frequency of the scanning subsystem is about 2.2 kHz. In fact, there are more than 2000 frames of beam current signals shown in the beam monitor. Thus, real-time beam-map monitoring by using image processing is not feasible using currently available techniques.

A guideline for a good implantation of the beam scan setup, obtained from experienced operators, is expressed in words as

> "The outermost edge of the beam map should be *centered* and *symmetric* on the beam monitor, with *appropriate width*, and the minor curves below the outermost edge should be *symmetric*."

According to this guideline, operators have to manipulate four joysticks to adjust the voltage being applied to the vertical and horizontal scan plates, which control the centering and magnitude of the ion beam, to obtain good implantation over the wafers. From the beam tuning guideline and the beam map shown in Fig. 2, four key features can be summarized in recognizing the beam map: the *width* of the beam map, the *centering* of the beam map, and the *symmetry* of both the outermost and the minor curves of the beam map.

To represent these features, the frames of a beam map are categorized into two sets: the outermost edge, and other minors below the outermost edge, as shown in Fig. 3. Each frame in the beam monitor is further segmented into the left segment, the center segment, and the right segment, which are represented by the quantitative sequences $L(k)$ and $l(k)$, $C(k)$ and $c(k)$, and $R(k)$ and $r(k)$, respectively, where index k represents the kth frame; the upper-case sequences represent the outermost edge, and the lower-case sequences represent the minors.

In Fig. 3, the width of the beam map can be obtained by measuring the period of $C(k)$, the centering of the beam map can be specified by evaluating the difference between $R(k)$ and $L(k)$, the symmetry of the outermost edge of the beam map is related to the variance of $R(k)$ and $L(k)$, and the symmetry of the minor curves in Fig. 2 can be estimated by calculating the variance of $r(k)$ and $l(k)$. As a result, the features for recognizing a *centered* and *symmetric* beam map with *appropriate width* can be obtained as

F_1: mean of $\{C(k)\}$;
F_2: mean of $\{L(k)\}$ – mean of $\{R(k)\}$;
F_3: variance of $\{L(k)\}$ + variance of $\{R(k)\}$;
F_4: variance of $\{l(k)\}$ + variance of $\{r(k)\}$.

By obtaining the quantitative sequences $L(k)$ and $l(k)$, $C(k)$ and $c(k)$, and $R(k)$ and $r(k)$, beam map recognition can be achieved. Instead of using complicated image-processing techniques, this paper presents a low-cost data-acquisition technique that can represent the 2-D beam map simply by 1-D sequences.

3. Data-acquisition system

The beam current signal and the display blanking signals form a beam map. Fig. 4 shows the timing of the beam current signal Y, the blanking signal BLK, and the corresponding beam map. The Y represents ions per second implanted into a wafer, and the BLK controls the display of the beam current on the beam monitor. When the BLK goes low, the beam current Y is displayed on the beam monitor. Moreover, the phase difference between the Y and BLK determines the relative position of the beam current on the beam monitor. In other words, the timing of BLK can be used as a base-line to specify the relative position of the beam map displayed on the beam monitor. Fig. 5 illustrates the segmentation technique used to obtain the periods of the left, center, and right segments by counting the pulse width of each segment in the CLK-base. Thus, the features of F_1, F_2, F_3, and F_4 are obtained, and the pattern recognition of the 2-D beam map is simplified to a 1-D digital signal processing.

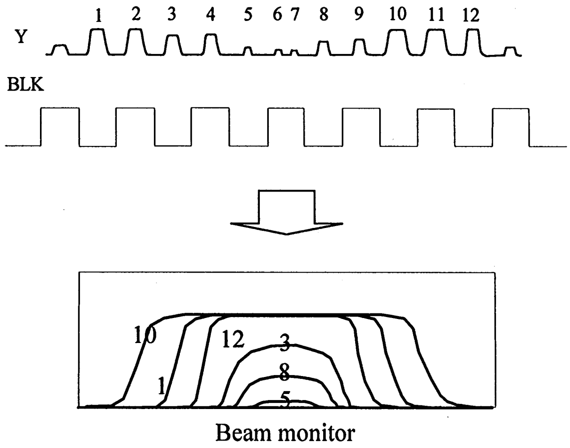

Fig. 4. The timing of the beam map display.

4. Symptom generation of the beam scanning

By using the hardware developed in Section 3, as illustrated in Fig. 5, the features of F_1, F_2, F_3, and F_4 are efficiently obtained. Therefore, a qualitative model for the beam-map recognition can be constructed as follows:

4.1. Qualitative model for beam-map recognition

1. If F_1 is MEDIUM, then the width of the beam map is APPROPRIATE.
2. If F_1 is SMALL, then the beam map is too NARROW.
3. If F_1 is LARGE, then the beam map is too WIDE.
4. If F_2 is ZERO, the beam map is CENTERED.
5. If F_2 is POSITIVE, the beam map is off-center to the RIGHT.
6. If F_2 is NEGATIVE, the beam map is off-center to the LEFT.
7. If F_3 is SMALL, the beam map is SYMMETRIC.
8. If F_3 is LARGE, the beam map is ASYMMETRIC.

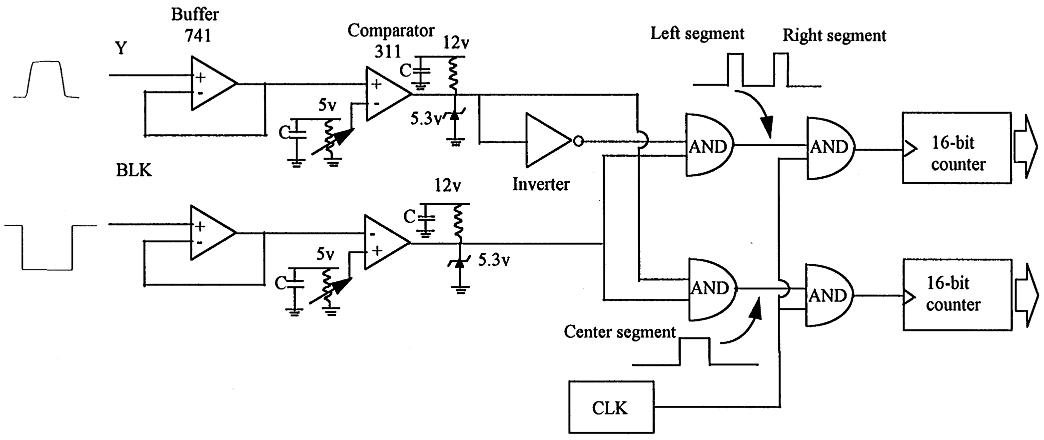

Fig. 5. Hardware of the data acquisition of the beam map display (Shen, 1998).

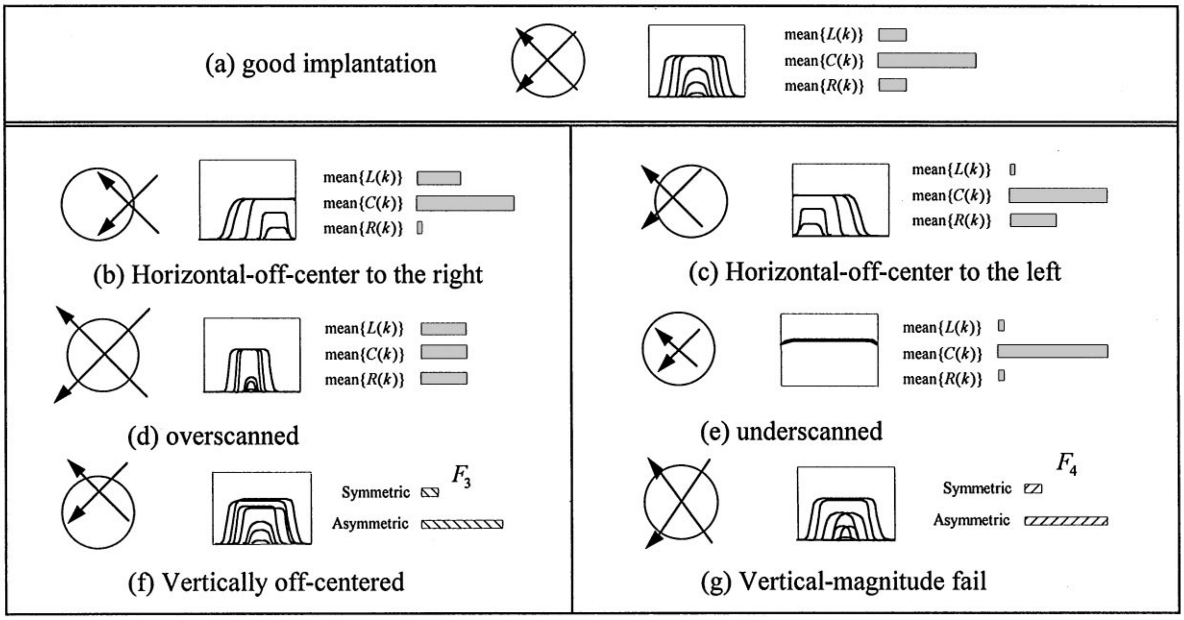

Fig. 6. Schematic symptoms of abnormal beam scans.

9. If F_4 is SMALL, the minors of the beam map are SYMMETRIC.
10. If F_4 is LARGE, the minors of the beam map are ASYMMETRIC.

Moreover, the differences between these features and the reference values can be used to identify the symptoms of non-uniform beam scans.

Since specific centering and magnitude voltages, applied to the vertical and horizontal scan plates, generate a specific beam-scanning pattern on the wafer, conditions of bad implantation can be identified by using the beam map display. Fig. 6 gives the symptom analysis corresponding to abnormal beam scan conditions, based on the estimated features of F_1, F_2, F_3, and F_4. For example, in the case of (c), negative F_2 relates to beam scanning that is off-center horizontally to the left. In the case of (d), the small F_1 maps to an overscanned ion beam.

5. The fuzzy expert system for decision making

According to the symptom analysis, the knowledge of experienced engineers, and the proper operating menu of the machine, the rules for a beam-scan setup can be summarized as follows.

5.1. Rules for beam-scan adjustment

1. If the ion beam is UNDERSCANNED, then the Horizontal-Magnitude should be tuned UP.
2. If the ion beam is OVERSCANNED, then the Horizontal-Magnitude should be tuned DOWN.
3. If the ion beam is off-center to the LEFT (RIGHT), then the Horizontal-Center should be tuned RIGHT (LEFT).
4. If the Vertical scanning range is UNDERSCANNED or OVERSCANNED, then the Vertical-Magnitude should be adjusted.
5. If the Vertical scanning center is UNCENTERED, then the Vertical-Center should be adjusted.

Because the tuning knowledge about the beam setup varies according to different operators, an intelligent supervisory system compromising different expertise was developed by using fuzzy theory. A typical fuzzy expert supervision system consists of five major parts: (a) a fuzzifier, which relates real numbers to fuzzy sets; (b) an inference engine, which performs fuzzy reasoning using the fuzzy diagnostic rules; (c) a data base, which provides the inference engine with the membership functions of the fuzzy sets used in the rule base; (d) a rule base, which provides the inference engine with fuzzy diagnostic rules; and (e) a defuzzifier and explanation facility, which transforms the outcome of fuzzy inferences from fuzzy sets into real numbers to provide operators with the beam setup tuning index. Moreover, advice to maintain the machine is also provided. The real-time intelligent beam-map supervisory system is constructed as shown in Fig. 7.

The Data Examining subsystem is an intelligent information filter, which justifies the confidence level of a decision based on input data, by using the following rule:

> “The confidence level of each decision is proportional to the rate of valid data in the input data stream.”

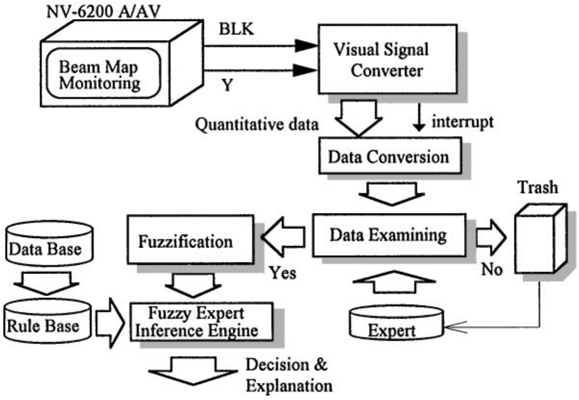

Fig. 7. The present intelligent supervision system.

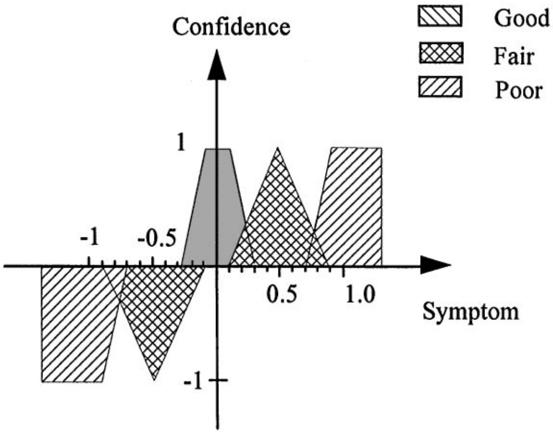

Fig. 8. The membership function of symptoms obtained by features F_1 and F_2.

The symptoms from the features of F_1, F_2, F_3, and F_4 and reference values are the four fundamental variables adopted in the fuzzification. Figs. 8 and 9 show the commonly used triangle-like membership functions of the input variables which are constructed in the Data Base. Note that the positive confidence level in Fig. 8 represents that the ion beam is off-center to the right, and the negative confidence represents an off-centeredness to the left. To achieve a compromise between the decision accuracy and experience of well-trained operators, a dead-zone is used in the region of 'Good' to avoid a too conservative threshold.

Since the input variables (features) are normalized, and each feature is independent from the others in recognizing the centering and amplitude of the vertical and horizontal beam scanning, the Fuzzy Expert Inference Engine here can simply use the weighted fuzzy sum as

$$\text{Suitability}_i = \sum_i \text{weighting}_i \times \text{rating}$$

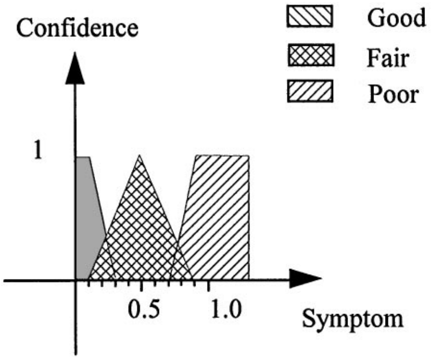

Fig. 9. The membership function of symptoms obtained by features F_3 and F_4.

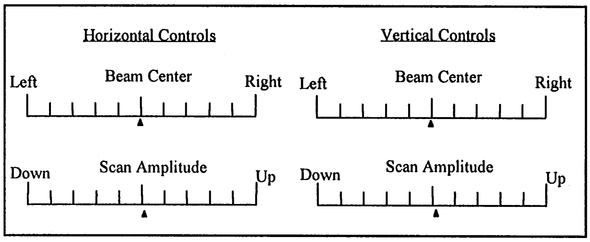

Fig. 10. Tuning indices of beam scan setup in uniform implantation.

Fig. 11. The intelligent supervision system.

to form a decision base. The tuning experiences of operators on beam-scan setup are acquired and stored in the rule base for supervising the scan pattern adjustment. The output is connected to a display for tuning indices as shown in Figs. 10 and 11 to provide computer-aided training for operators. Note that in normal implantation, the solid triangles in Fig. 10 will all appear around the center position. For instance, if the triangle on the 'Beam center' in 'Horizontal controls' is shifted to the 'Right', this means that the horizontal beam center control needs to be moved to the left. On the other hand, if the triangle on the 'Scan amplitude" in 'Horizontal controls' is closer to the "Down", it means that the horizontal scan amplitude control needs to be moved up.

6. Experimental results

Two experimental examples of supervising error operations are given as follows:

Case 1 (Overscanned ion beam): Fig. 12 shows the beam map of an overscanned beam scan pattern, and Fig. 13 provides the tuning indices, which indicate that a decrease in the scan amplitude is required.

Case 2 (Uncentered beam scans with vertically imbalanced amplitude): Fig. 14 shows the beam map of a beam scan pattern that is both horizontally off-center to the right and vertically amplitude imbalanced. The corresponding adjustments advised by the supervisory system are provided as in Fig. 15, which indicates both that the beam center joystick should be moved to the left, and that the vertical scan amplitude should be tuned to keep the triangle approaching the center position.

The results in Cases 1 and 2 show that the adjustments suggested by the supervisory system are consistent with the operating menu (Eaton Corp., 1992) to obtain uniform beam scans. The complete supervisory system is implemented on an industrial personal computer, which achieves on-line monitoring on the implantation process in IC fabrication as shown in Fig. 16.

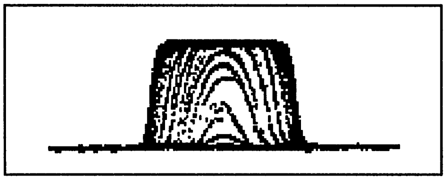

Fig. 12. The beam map of an overscanned scan pattern.

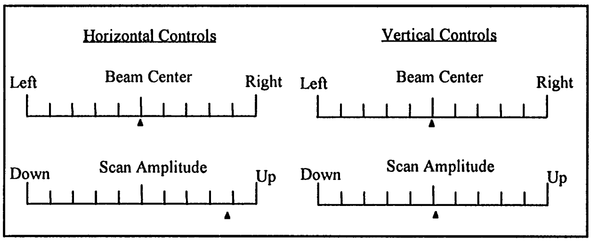

Fig. 13. The tuning indices for Case 1.

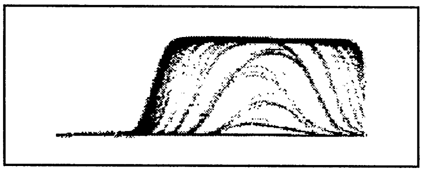

Fig. 14. The beam map of an uncentered beam scan with a vertically imbalanced scan amplitude.

7. Conclusion

Monitoring of semiconductor equipment to prevent loss of wafers is a crucial task to increase the yield rate and the productivity in IC manufacturing. In this paper, by applying a feature-extraction technique, a special data-acquisition system has been developed to simplify the 2-D beam map recognition into a 1-D feature classification. Based on the 1-D features of the beam map, a qualitative feature model of beam-map recognition is obtained to achieve real-time beam-map recognition. The qualitative model is used for symptom generation in monitoring the beam scanning. Moreover, the analysis of abnormal symptoms provides rules for beam scanning and decision making. The proposed intelligent supervisory system has been successfully applied to the beam-scan subsystem of the Eaton NV-6200 A/AV ion implanter at the Taiwan Semiconductor Manufacturing Company (tsmc) for monitoring the ion implantation process and providing the computer-aided beam-scan setup.

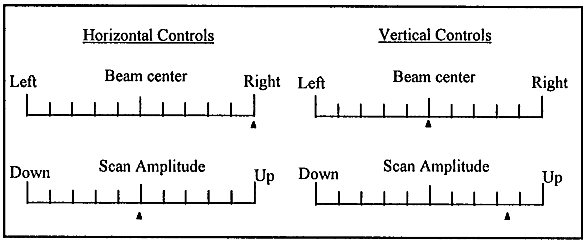

Fig. 15. The tuning indices for Case 2.

Fig. 16. On-line implementation on the ion beam implanter.

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