Yield Improvement of a Large Area Magnetic Field Sensor Array Design Using Redundancy Schemes

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Abstract

Design of a Large Area Magnetic Field Sensor Array (LAMSA) using redundancy schemes concurrently with the laser link technology for fault repairs is presented. Experimental results obtained on a laser restructurable subarray of three magnetic field sensor cells are shown. An experimental yield measurement method to determine parameters of two yield detractors is described. These parameters obtained from regular sized VLSI chips are used to predict the yield of larger sensor array designs implemented with redundancy.

1. Introduction

Previously, wafer scale integrated circuits have been successfully built by using laser interconnection techniques for defect avoidance after fabrication[1]. Currently, designs of large area transducer arrays such as thermal pixel scene generator[2] and magnetic field sensor array[3] are progressing. These systems are implemented by using the same laser interconnection post fabrication techniques added to micromachining post processing.

The Large Area Magnetic Field Sensor Array (LAMSA)[3] is formed of a sensor grid, surrounded by control circuits which include: shift-registers, amplifiers, transmission gates and cascode current mirrors, as shown in Figure 1. Similar to wafer scale integrated circuits, this design also requires levels of redundancy to restructure, after fabrication, faulty cells or blocks, thus increasing the yield of the sensor array. However, contrary to conventional wafer scale circuits, where generally global schemes of redundancy are employed, here local redundancy must be used for the sensor grid due to the sensor position dependency. Still, in the case of surrounding control circuits, more flexible redundancy schemes of a global nature can be used.

The unique dual redundancy characteristic of the LAMSA design has not yet been clearly addressed. In this paper the design of a regular VLSI chip size version of the LAMSA, which has been submitted for fabrication, is described. As well as testing the LAMSA operation, this chip will explore the redundancy problem by experimentally determining yield detractor parameters affecting the sensor grid and the control circuits. Thus, from yield measurements performed on identical chips, an analytical yield expression including the effect of redundancy is defined and will be used to predict the yield of LAMSA designs of given area.
and redundancy scheme.

In section 2 we describe the basic principle of operation of the LAMSA. Section 3 presents the redundancy levels of the design and experimental results obtained on a laser restructurable subarray of three sensors. The experimental measurement method used to determine parameters of the defect density distributions is explained in section 4. From those measured parameters, an analytical yield expression, including the effect of redundancy is developed in section 5. Finally, examples of design yield improvement using redundancy are given in section 6.

2. LAMSA Principle of Operation

Figure 1 shows the floor plan of the LAMSA. The magnetic field sensor grid is made of a matrix of rows and columns of double drain/double source merged Mosfet (Figure 1 inset). The magnetic response of each magnetic sensor cell (MSC) is read in a raster scan fashion, synchronized by column and row shift registers. Signal lines directing each MSC to the cascode current mirror used as biasing circuit are activated by bidirectional transmission gates which are controlled by the column shift register[3]. A differential amplifier (amp.) is used to amplify MSC responses.

Figure 1. Floor plan of the LAMSA. Inset: 3 merged sensor cells.
Figure 2 shows current paths commanded by the column shift register, which enable the reading of the magnetic field response of the sensor MSC2. MSC2 is the middle sensor cell of a 3 merged sensor cell subarray. Note that this subarray can be located anywhere in the grid as illustrated in Figure 1. The purpose of using merged sensor cells is to reduce the number of gate and drain/source connections required to read each MSC response[3]. The proper row to be read is selected by the outputs of the row shift register which turns “on” the gates of all the MSCs in the entire row. By propagating a “0” at the outputs of the column shift register which are initially set to “1”, the current flowing from the cascode current mirror is directed by the bidirectional transmission gates (BTGs) to only one MSC at a time, thus performing a sequential reading of the MSCs. In the case of Figure 2, the presence of a magnetic field will produce a difference between the amplitudes of currents \( I_{D1} \) and \( I_{D2} \) flowing through drains D1 and D2 of MSC2, which creates a voltage difference at the outputs of the current mirror. This voltage difference is accessible through lines Da and Db which feed the input of a differential amplifier.

![Diagram of current paths](image)

**Figure 2.** Current paths involved in the reading of the sensor cell MSC2. CSR1 and CSR2 are set to “0” while CSR3, CSR4 and RSR1 are set to “1”.

3. **Redundancy Levels of the LAMSA Design**

3.1. **Device function criteria**

The philosophy of defect avoidance in the LAMSA is to create a design which targets the maintenance of specified transducer resolution throughout the array. The design will allow some local failures, however it has to be resistant to defects that could eliminate large areas of the system.
As we can see in the floor plan of Figure 1, each type of control circuit surrounding the sensor grid is duplicated at least one time providing a global redundancy of 2:1. The physical position of the working circuits is not critical for the device to function well. They can be on any side of the large chip.

Conversely, the sensor grid redundancy pattern can not be global, because each physical region of the grid needs a certain number of working cells. Figure 3 presents an enlargement of the sensor grid. Here, at the pixel level, a local redundancy of 3:1 is defined, meaning that at least one MSC out of three in the same pixel block has to be non-defective to consider the pixel functional. For a given application, MSCs are fabricated at twice the linear minimum resolution of the final system target. With yields of individual MSC being easily 99%, it means that most of the array will have more resolving power than the minimum amount required. Defect clustering may lead to a few sites with no resolution. Although, this is acceptable in many transducer applications. Indeed CCD arrays are priced for sale in terms of the number of defect points within the array.

![Diagram of sensor grid redundancy](image)

**Figure 3. Detail of the pixel redundancy**

To increase the sensor grid yield, another redundancy scheme is added at the sensor cell level. Figure 4a) shows the signal line redundancy pattern for the three merged sensor cells structure. Here, for each MSC, the redundancy scheme allow four possible connections between a drain/source contact and a drain/source signal line and two possible connections between the gate and a gate signal line. This prevents any signal line failure from eliminating a whole column or row of sensors. Figure 4b) shows a photomicrograph of the three merged sensor cells structure along with laser link interconnections implemented to achieve the signal line redundancy pattern. Since the laser link principle consists of creating a laser-diffused link between two active regions[1], laser link structures are directly merged to drain/source implants. This test subarray has been fabricated under the Mitel 1.5μm process. Note here that no gate redundancy has been included. Each sensor takes an area of 54 x 54 μm.
3. 2. Experimental Results

Sensitivity measurements have been carried out on the test structure of figure 4b). Previously, the eight drain/source diffusion regions have been laser-linked to eight signal lines. Then, the sequential reading of each MSC response has been achieved on the same manner as described in section 2. The only difference involved here is that the sequential switching of pairs of signal lines between the ground and the cascode outputs has been performed manually instead of using bidirectional transmission gates.

![Diagram](image)

Figure 4. a) Detail of the signal line redundancy scheme for three merged sensor cells. b) Photomicrograph of the sensor subarray structure implemented with laser links for drain/source signal line redundancy.

The graph of Figure 5 shows the responses of three merged sensor cells exposed to a magnetic field of 1700 Gauss as a function of the voltage applied on their common gate. These curves correspond to the voltage difference created by the magnetic field between the cascode current mirror outputs which can be accessed through lines Da and Db (see Figure 2). Responses of the two outer cells MSC1 and MSC3 are similar, while the one of the middle cell MSC2 is higher. Due to its center subarray position, the different electrical field topology surrounding MSC2's drains and sources enhances the current splitting effect of the sensor,
which causes the higher sensitivity observed. However for a gate voltage of 1.12V, which corresponds to the peak sensitivity of MSC1, responses of the three cells are of the same order of magnitude: MSC1 = 75.9 mV, MSC2 = 112.1 mV and MSC3 = 76.6 mV.

4. Yield Parameters Measurement Method

The success of a large version of the LAMSA design is closely related to the yield of the technology used. To help the design task, we develop a yield expression, where parameters are extracted from experimental measurements on regular sized chips implemented on the targeted technology. The main goals of these test chip will be: 1) testing of sensor and control circuit operations and 2) extraction of basic yield parameters. To facilitate these tasks, no redundancy is included in this first design.

![Graph showing VDa-VDb vs Gate Voltage](image)

**Figure 5. Magnetic field response (VDa-VDb) vs gate voltage of a three merged sensor cells subarray.**

Figure 6 shows the physical layout of the LAMSA, where a sensor grid of 27 rows x 35 columns is designed with a 36 bits shift register and 36 transmission gates above controlling 36 pairs of contacts. The whole chip including the output pads is 3.1 x 3.1 mm large and a single sensor cell is 54 x 54 μm. The sensor grid density is 176 sensor cells/mm².

Extraction of the sensor grid yield parameters is based on the identification of two kinds of defects producing a faulty sensor cell. One is related to faults due to signal lines and the other identifies faults due to sensor cell devices excluding the signal lines and their connections. According to the high symmetry of the sensor grid, where columns and rows of sensor cells are interconnected together through common signal lines, faults due to signal lines will most likely affect more than one cell. Hence, they will be easily identified. Thus, it is possible two yield detractors: $Y_{se}$ for the sensor element without the signal lines; and $Y_{sl}$ for the signal lines on top or beside the sensor element. Each of these yield detractors has its own distribution of defect density.
The defect density distribution expression used is the negative binomial which has given excellent results in cases where clustering is observed[4]. The probability to obtain a cell with \( x \) defects due to the sensor element or signal lines is given respectively by:

\[
P_{se}(x_{se}) = \frac{\Gamma(\alpha_{se} + x_{se})}{x_{se}!\Gamma(\alpha_{se})} \left( \frac{A\lambda_{se}/\alpha_{se}}{1+A\lambda_{se}/\alpha_{se}} \right)^{x_{se} + \alpha_{se}}
\]

(1)

\[
P_{sl}(x_{sl}) = \frac{\Gamma(\alpha_{sl} + x_{sl})}{x_{sl}!\Gamma(\alpha_{sl})} \left( \frac{A\lambda_{sl}/\alpha_{sl}}{1+A\lambda_{sl}/\alpha_{sl}} \right)^{x_{sl} + \alpha_{sl}}
\]

(2)

where \( \lambda_{se}, \lambda_{sl} \) are the defect density parameters, \( \Lambda \) the defect sensitive area and \( \alpha_{se}, \alpha_{sl} \) the clustering parameters. According to the results of Stapper and Rosner[5] obtained on Read Only Store chips, simplistic yield models give better results when the fitting is modeled for \( \lambda \) expressing the number of defects per cell, especially for designs made of mainly one type of cell such as memory circuits and our sensor grid. The yield is then given by the probability of having 0 defect:

\[
P_{se}(0) = Y_{se} = \left( 1 + n\lambda_{se}/\alpha_{se} \right)^{-\alpha_{se}}
\]

(3)

\[
P_{sl}(0) = Y_{sl} = \left( 1 + n\lambda_{sl}/\alpha_{sl} \right)^{-\alpha_{sl}}
\]

(4)

where \( \lambda_{se}, \lambda_{sl} \) now express the number of defects per cell and \( n \), is the number of cells included
in the yield calculation. The method employed to extract parameters $\lambda_{ct}$, $\lambda_{pl}$, $\alpha_{ct}$ and $\alpha_{pl}$ is called the window method[4] which consists of measuring yields of different blocks of identical chips from several wafers, plotting the yield as a function of the number of chips per block, and obtaining parameters $\lambda$ and $\alpha$ from a nonlinear regression analysis. This method has given good results when large area clustering is observed meaning when the parameter $\alpha$ is the same for all different numbers of chips per block. According to Stapper[6] this condition is often satisfied since most of the clustering is expected to occur from wafer to wafer variations of fault densities indicating a clustering area equal to the wafer size.

Analogous to this method, in our case, chips are replaced by sensor cells, and wafers by chips. Thus the large area clustering assumption should be even more valid since we measure yields of blocks of cells much smaller than the wafer. Figure 6 shows an example of 3 different blocks of cells sizes which can be used to measure three yield values $Y(n_1)$, $Y(n_2)$ and $Y(n_3)$. For our measurements, a sample data of 35 chips is expected. The yield measurement algorithm has to be performed independently for each yield detractor $Y_{se}$ and $Y_{sl}$. This method will not be able to identify cluster defects connected to specific areas, such as the outer edges of the wafer.

In the case of the control circuits, the yield of every type of modules will be measured separately without discrepancy between signal lines defects and device defects. The redundancy type of these modules being global is not discussed in this paper since it has been extensively addressed in the past[4].

5. Yield Improvement Using Redundancy.

Once parameters $\lambda$ and $\alpha$ have been determined for both distribution, effects of pixel and signal line redundancy schemes, as shown in Figure 3 and Figure 4a) respectively, on the yield expression can be included. At the cell level, the cell yield $Y_{cell}$ becomes:

$$Y_{cell}(n) = Y_{se}(n) \sum_{\text{allfixable}} P_{sl}(n, x_{sl})$$

(5)

The term $Y_{se}$ is included directly in equation 5, since there is only one sensor element per cell, hence, no fixable pattern is possible for the sensor element at the cell redundancy level. However, several $P_{sl}$ terms must be summed since several fixable patterns are possible. For instance, according to the signal line redundancy scheme of Figure 4a), each pair of drain/source contacts have four possible line connections and two possible lines are available to connect the gate. Thus, there are ten possible signal lines for five required connections, meaning that up to five defective lines per cell can be avoided. Hence equation 5 becomes:

$$Y_{cell}(1) = Y_{se}(1) \left[ P_{sl}(1, 0) + P_{sl}(1, 1) + \frac{44}{45} P_{sl}(1, 2) + \frac{104}{120} P_{sl}(1, 3) + \frac{132}{210} P_{sl}(1, 4) + \frac{78}{232} P_{sl}(1, 5) \right]$$

(6)

Factors before $P_{sl}$ terms are ratios of fixable patterns over total numbers of available patterns for each amount of signal line defects. For $n = 2$ and $3$, the maximum number of signal line defects that can be avoided is 9 and 14 respectively. The pixel redundancy is then given by[4]:

$$Y_{pix} = \sum_{i=0}^{R} (-1)^{R-i} \binom{N}{N-1-i} \binom{N-1-i}{N-R-1-i} Y_{cell}(R-i)$$

(7)
where \( N \) is the total number of cells and \( R \) the number of spares. Having defined a pixel redundancy of 3:1 meaning \( N=3 \) and \( R=2 \). Finally, for a grid containing \( K \) pixels, the final grid yield is simply given by:

\[
Y_g = Y_{pix}^K
\]

6. Example of Sensor Grid Yield Improvement Using Redundancy

The following example is a yield calculation of a magnetic sensor grid of \( 1 \text{cm} \times 1 \text{cm} \) made up of 17,600 cells with a pixel redundancy of 3:1. To obtain a tangible variation of the pixel redundancy, an exaggerated average number of signal line defects per cell \( \lambda_{sl} \) and sensor element defects per cell \( \lambda_{se} \) of 0.05 have been employed. Table 1 shows the variation of the pixel and grid yields for a grid having full redundancy and no signal line redundancy as a function of the signal lines clustering coefficient \( \alpha_{sl} \), where \( \alpha_{se} = \infty \) (i.e. no defect clustering). Table 2 shows the same variation as a function of the sensor element clustering coefficient \( \alpha_{se} \), where \( \alpha_{sl} = \infty \).

<table>
<thead>
<tr>
<th>( \alpha_{sl} )</th>
<th>( Y_{pix} )</th>
<th>( Y_{grid} )</th>
<th>( Y_{pix} )</th>
<th>( Y_{grid} )</th>
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<td>99.977</td>
<td>26.634</td>
<td>99.913</td>
<td>0.607</td>
</tr>
</tbody>
</table>

Table 1. Pixel and grid yields as a function of the clustering coefficient \( \alpha_{sl} \) of the signal line defect distribution for \( \lambda_{se} \) and \( \lambda_{sl} \) of 0.05 and \( \alpha_{se} = \infty \).

<table>
<thead>
<tr>
<th>( \alpha_{se} )</th>
<th>( Y_{pix} )</th>
<th>( Y_{grid} )</th>
<th>( Y_{pix} )</th>
<th>( Y_{grid} )</th>
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</thead>
<tbody>
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<tr>
<td>( \infty )</td>
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<td>26.634</td>
<td>99.913</td>
<td>0.607</td>
</tr>
</tbody>
</table>

Table 2. Pixel and grid yields as a function of the clustering coefficient \( \alpha_{se} \) of the signal line defect distribution for \( \lambda_{se} \) and \( \lambda_{sl} \) of 0.05 and \( \alpha_{sl} = \infty \).
Results clearly show the importance of the signal line redundancy in the yield improvement. At high clustering, sensor element defects have more impact on the degradation of the yield than signal line defects. Also, values of grid yields are underestimated especially at high clustering, since in equation 8 the clustering effect is taking into account through $Y_{pix}$, meaning that only three cells are considered by the defect distribution instead of the whole grid.

7. Conclusion

Experimental results obtained on a sensor subarray linked to signal lines by laser links prove the feasibility of signal line redundancy schemes to improve the sensor grid yield. Calculations clearly show the importance of the signal line redundancy scheme for the sensor grid yield improvement. However, for larger devices, more accurate calculations will have to include the effect of different clustering sizes. The main purpose of the yield expression developed in this paper is to help in the design of redundancy schemes at different levels to achieve reasonable yield of the large area magnetic field sensor array device. Since the calculation is performed from measured yield parameters on chips fabricated on the targeted technology, extrapolation of device yields for gradual enlargement of device sizes will be possible. Test chip designs have been submitted for fabrication. In addition of testing the control circuits involved in the LAMSA operation, they will give important information on the main types of defects occurring in the Mitel 1.5μm process.

References


