Multirow writing method for massively-parallel electron-beam systems

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Electron-beam (e-beam) systems with a large number of beams have been developed in order to improve the writing throughput. It is desirable to have a writing method which can control beams to achieve not only a high throughput but also a high quality of writing. In a massively-parallel e-beam system, it is unavoidable that some beams are faulty and the current may vary with the beam. An important issue is how to mitigate the effects of faulty beams and current variation to enhance the quality of a transferred pattern. A possible way to reduce the negative effects of faulty beams is to spread the effects spatially. In this paper, a writing method, referred to as *multirow writing*, which uses each beam to expose pixels over multiple rows in each writing path, is proposed and the general procedures of realizing the method is described. The multirow writing method minimizes the dose reduction at a pixel and localization of affected pixels without exposing each writing path multiple times. *Published by the AVS.* https://doi.org/10.1116/1.5122673

I. INTRODUCTION

An electron-beam lithographic system with multiple beams has been considered to be a solution for improving the writing throughput significantly.[1,2] The massively-parallel electron-beam systems recently developed are equipped with a large number of beams which can be turned on and off individually.[3,4] An important issue, in addition to the maximization of writing speed, is to achieve a high quality of writing result. When there are a larger number of beams in a system, e.g., 2^{18} beams as in the electron multi-beam mask exposure tool (eMET),[3] it is more likely that some of the beams are faulty. Also, the beam current may have a substantial variation among beams. In order to optimally utilize such a system, it is essential to understand the effects of faulty beams and current variation and develop a method which can minimize any negative effect on the writing quality.

In a writing strategy of the eMET, a beam follows and exposes a pixel multiple times, referred to as "trotting."[5] Therefore, when a beam is faulty, it can reduce the dose received by a pixel significantly. In another writing strategy, a group of beams jointly exposes each pixel to mitigate the effect of a faulty beam and increase the dose range. However, in both strategies, a beam is confined to a single row in each writing path (to be referred to as *single-row writing*), which makes the effects of faulty beams localized in the respective rows. The more the effects are localized, the larger the spatial variation of dose, and, therefore, exposure (energy deposited in the resist), become, potentially leading to a lower quality of writing.

In this study, a writing method referred to as *multirow writing*, which minimizes the spatial localization and dose reduction of affected pixels, and general procedures of realizing the method are developed. The writing method allows pixels in multiple rows to be exposed by a beam in each writing path in order to spread affected pixels and decrease the number of times a pixel is exposed by a beam. This paper focuses on the realization of the method, including the derivation of required conditions. In another study, through an extensive simulation, the effects of abnormal (faulty) beams on the writing qualities such as critical line edge roughness and maximum indent are analyzed and the multirow writing is shown to perform significantly better than other writing methods in terms of the writing qualities.

Compared to the single-row writing, the multirow writing method lowers the dose reduction for a pixel due to a faulty beam and localization of affected pixels. The multipass writing strategy[6] employed in a single-row writing method can achieve a similar improvement. However, it requires each writing path to be exposed multiple times and may result in a positioning error of beams between passes. Also, for the multipass writing to be effective, a positional shift of the substrate in the scanning direction needs to be added in each pass. The multirow writing method eliminates the need for multipass writing or can reduce the number of passes, i.e., it can be used along with the multipass writing to enhance its efficiency further.

The variation of beam current among beams is another important issue in a parallel-beam system. However, the effects of the variation would be similar to those of faulty beams and therefore may be analyzed in the same way. Hence, in this paper, the beam-current variation will not be considered separately.

In Sec. II, the effects of faulty beams are discussed. In Sec. III, the single-row writing methods and their properties are reviewed. In Sec. IV, the multirow writing and its realization are described, followed by the optimization of the multirow writing method in Sec. V. The single-row and multirow writing methods are compared in Sec. VI, and a summary is provided in Sec. VII.

II. EFFECTS OF FAULTY BEAMS

It is assumed in this study that the resist layer of a substrate system is on the X-Y plane and parallel beams are in

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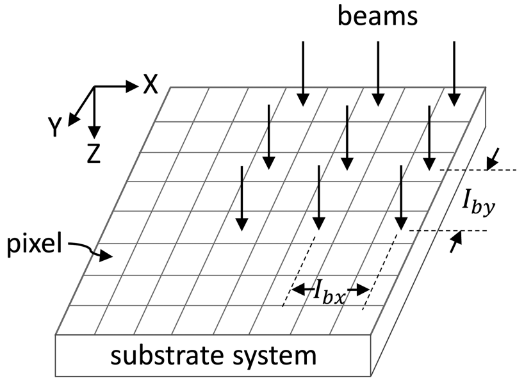

FIG. 1. Coordinate system employed in this study where I_{bx} and I_{by} are the beam intervals in the X and Y dimensions, respectively. The substrate moves in the X dimension (direction) being exposed by beams. Rows and columns (of pixels or beams) are in the X and Y dimensions, respectively.

the Z direction, i.e., normal to the X-Y plane, as illustrated in Fig. 1. *Rows* and *columns* of pixels or beams are in the X and Y dimensions, respectively. As in the eMET and MBM-1000,[6] beams can be individually turned on/off and all beams must be deflected in a synchronized manner, i.e., the same angle and direction. The dose given to a pixel by a faulty beam would be different from, mostly lower than, the dose that a normal beam is supposed to give. For the convenience of analysis, it is assumed that a faulty beam is not able to give any dose to pixels, i.e., gives a dose of zero.

The effects of faulty beams may be considered in two aspects. One is the reduction in the dose received by an individual pixel, and the other is the spatial distribution of the affected pixels. Let D denote the total dose to be given to a pixel and D_a the actual dose received by the pixel as illustrated in Fig. 2. The dose reduction for a pixel due to faulty beams is denoted by ΔD, i.e., $\Delta D = D - D_a$. The larger the ΔD is, the pixel is less likely to be developed. The ΔD is larger when the number of times a pixel is exposed by a faulty beam (or faulty beams) is greater. Therefore, in order to minimize ΔD, the number of times a faulty beam exposes a pixel needs to be minimized.

When an affected pixel is farther away from other affected pixels, it has a better chance to be developed. On the other hand, affected pixels adjacent to each other are likely to be underdeveloped or not developed since they can form a

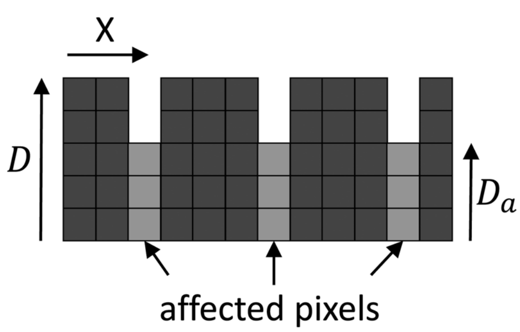

FIG. 2. Pixel affected by a faulty beam receives a dose D_a lower than the target dose D.

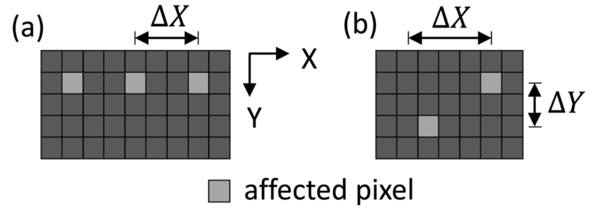

FIG. 3. Displacement vector (ΔX, ΔY) in (a) the single-row writing and (b) the multirow writing.

contiguous region where the exposure level is significantly lower than the normal level. Hence, to minimize the effects of faulty beams, it is necessary to spread the affected pixels spatially as much as possible, i.e., minimize the spatial localization of affected pixels. The displacement vector between the two closest affected pixels is denoted by (ΔX, ΔY) where ΔX and ΔY are represented in pixel, as shown in Fig. 3. The larger the ΔX and ΔY are, the less the localization of affected pixels is. In this study, the displacement vector is considered for pixels affected by a faulty beam (not multiple faulty beams).

III. SINGLE-ROW WRITING

Single-row writing refers to a writing method where each beam is allowed to expose pixels in one row only in each writing path.[3] The substrate is moved in the X dimension during the exposing process of each horizontal strip and shifted up in the Y dimension for exposing the next strip. In a *step*, a beam gives a unit dose of d to a pixel. A *cycle* consists of n_s steps and may be repeated n_c times to give the (total) dose of D to a pixel, i.e., $D = n_c n_s d$. When $n_c > 1$, each pixel is exposed by n_c different beams. For the single-row writing, $\Delta Y = 0$ as illustrated in Fig. 3(a).

Single-row I: Consider the trotting method where a beam exposes a pixel n_s times in a cycle where $n_s > 1$ [refer to Fig. 4(a)]. When $n_c = 1$, a pixel exposed by a faulty beam misses the unit dose n_s times, i.e., $\Delta D = n_s d$. When $n_c > 1$, ΔD depends on the number of faulty beams, n_f, among n_c

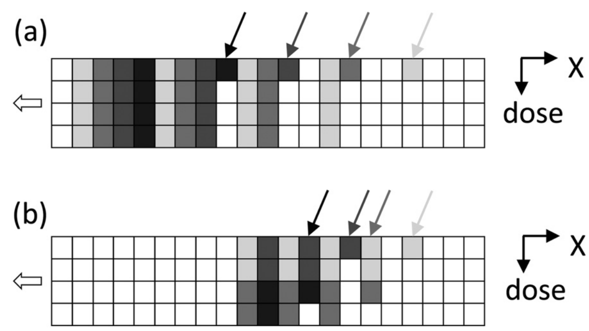

FIG. 4. In the single-row writing, each beam exposes pixels in a row only. (a) Single-row writing I: each beam follows ("trotting") a pixel exposing it n_s times ($n_s = 4$ in the above example) in a cycle. (b) Single-row writing II: a group of n_g beams ($n_g = 2$ in the above example) jointly exposes a pixel n_s times ($n_s = 4$ in the above example), n_s/n_g times per beam, in a cycle. The illustrations (a) and (b) are for the first and third steps in a cycle, respectively.

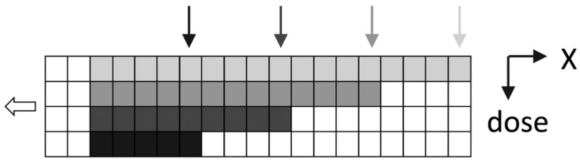

FIG. 5. Single-row writing III: to lower the dose reduction due to a faulty beam in the single-row writing, each beam may be allowed to expose each pixel only once. But, consecutive pixels are affected by a faulty beam.

beams exposing a pixel and $\Delta D = n_f n_s d$ where $1 \le n_f \le n_c$ and $n_c = D/n_s d$. $\Delta X = n_s$ since different affected pixels are spaced at the interval of n_s in a row. Note that ΔX may be considered to be 0 in that the same pixel is affected more than once.

Single-row II: In order to mitigate the effect of a faulty beam and also increase the dose range, a group of beams may jointly expose a pixel in a cycle [refer to Fig. 4(b)]. Let n_g be the number of beams in a group where $n_g > 1$. Then, when $n_c = 1$, $\Delta D = (n_s/n_g)d$. When $n_c > 1$, $\Delta D = n_f(n_s/n_g)d$ where $1 \le n_f \le n_c n_g$ and $n_c = D/n_s d$. Note that the number of beams exposing a pixel is $n_c n_g$. As for the single-row I writing method, $\Delta X = n_s$ since different affected pixels are spaced at the interval of n_s in a row. Note that ΔX may be considered to be 0 in that the same pixel is affected by more than once (assuming that $n_s/n_g > 1$).

Single-row III: As a way to reduce ΔD, n_s may be set to 1, i.e., each beam exposes a pixel only once (refer to Fig. 5). Then, n_c would be larger compared to the other methods (single-row I and single-row II), i.e., $n_c = D/d$. However, more beams have to be faulty to result in the same dose reduction since $\Delta D = n_f d$ where $1 \le n_f \le n_c$. That is, it is more likely that ΔD is smaller compared to the other methods. A drawback is that each beam needs to expose consecutive pixels and therefore affected pixels are adjacent to each other in a row, i.e., $\Delta X = 1$.

It needs to be pointed out that when nearby rows have one or more faulty beams, the distance between affected pixels can be smaller than the ΔX above depending on the relative locations of faulty beams in those rows.

IV. MULTIROW WRITING

A possible way to reduce the effects of faulty beams is to decrease the number of times a pixel is exposed by a beam and spread affected pixels spatially. This can be achieved by letting each beam expose a set of pixels distributed in both X and Y dimensions in each writing path. The spatial distribution of pixels in the set is referred to as *pattern*. The same pattern is followed by all beams in a system. In the case of single-row writing, beams are deflected only in the X direction in each writing path. But, for the multirow writing, beams need to be deflected in both X and Y directions. Since the beam-deflection sequence is the same for all rows of beams, the description of the writing method will be given for a row in most parts of this paper.

It needs to be mentioned that while the shape of the pattern would be mostly regular in practice, the multirow writing method is described for all possible shapes in this paper. Also, a pattern would be significantly larger than those in Figs. 6–9.

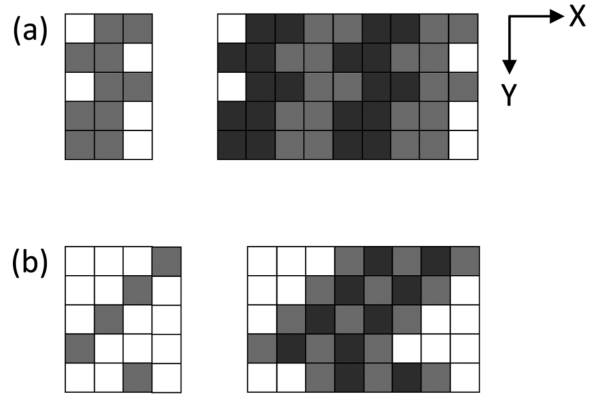

FIG. 6. Examples of stackable patterns: (a) $W_p = 2$, $H_p = 5$ and (b) $W_p = 1$, $H_p = 5$.

A. Stackability

A basic requirement is that a writing method must be able to achieve a uniform dose, i.e., give the same dose to all pixels within a feature or features.

Stackability: A pattern is said to be *stackable* if the pattern can be replicated and stacked together in the X dimension such that no hole or overlap is generated. Examples of stackable patterns are provided in Fig. 6.

For a pattern to be stackable, the following conditions must be met:

(i) All rows of the pattern have the same number of pixels.
(ii) Pixels in each row are consecutive.

The relative locations of pixel groups over rows can be arbitrary.

When a pattern not meeting condition (i) is replicated and stacked, there can be holes in the rows with less pixels than other rows in the pattern [as in Fig. 7(a)] and overlaps in the rows with more pixels. If condition (ii) is not met, there can be holes and overlaps in the rows where pixels are not consecutive [as in Fig. 7(b)]. Examples of unstackable patterns are provided in Fig. 7.

If a pattern is stackable, it is possible to achieve a uniform dose distribution using the pattern. The (effective) width of a stackable pattern is defined as the number of pixels in a row of the pattern, denoted by W_p. The height of a stackable pattern is the number of rows in the pattern, denoted by H_p. The size of a pattern, denoted by N_p, refers to the number of pixels in the pattern where $N_p = W_p H_p$. Then, a constant dose can be given to all pixels in the horizontal strip of which the width is H_p, using $N'_p \underline{\underline{\text{def}}} N_p/W_p = H_p$ beams in a row.

Note that N_p is equivalent to the length of a cycle, n_s, introduced earlier.

B. Beam interval

The beam interval in the X dimension is denoted by I_{bx} expressed in pixel. Let I'_{bx} denote the beam interval

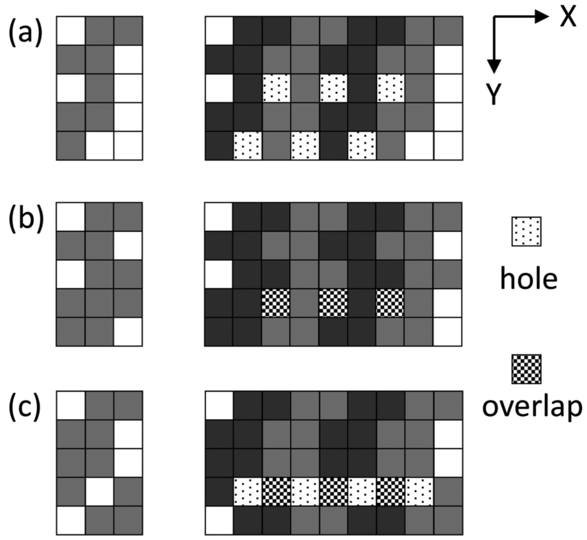

FIG. 7. Examples of unstackable patterns: stacking an unstackable pattern may generate (a) holes, (b) overlaps, or (c) holes and overlaps.

normalized by W_p, i.e., $I'_{bx} \underline{\underline{\mathrm{def}}}\, I_{bx}/W_p$. Then, the normalized beam interval I'_{bx} can be set to any coprime of H_p, realizing a uniform dose distribution. If I'_{bx} is not a coprime of H_p, there would be an overlap between a set of pixels exposed by a beam and that by another beam. Let h_p is a coprime of H_p where $h_p < H_p$. Then, $I'_{bx} = h_p + kH_p$ where k is a non-negative integer. That is, I'_{bx} can be less or greater than H_p. Hence, the beam interval I_{bx} must satisfy the condition below, to be able to realize a uniform dose distribution without any hole or overlap,

$$I_{bx} = W_p I'_{bx} = W_p(h_{p+} kH_p). \tag{1}$$

Examples with $W_p = 1$ and $W_p = 2$ are provided in Figs. 8 and 9, respectively. For the minimum spread of beams in the X dimension, $k = 0$. However, when there is a lower limit on the beam interval in a certain system, k may be selected to meet the lower limit.

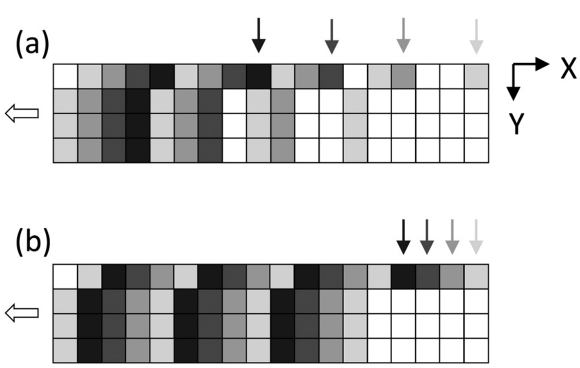

FIG. 8. Distribution of exposed pixels at the end of the first step in a cycle: (a) $I_{bx} = 3$ and (b) $I_{bx} = 1$. $W_p = 1$ and $H_p = 4$ for the pattern in this figure. The coprimes of $H_p = 4$ are 1 and 3. Therefore, 1 and 3 can be allowed as a beam interval, I_{bx}.

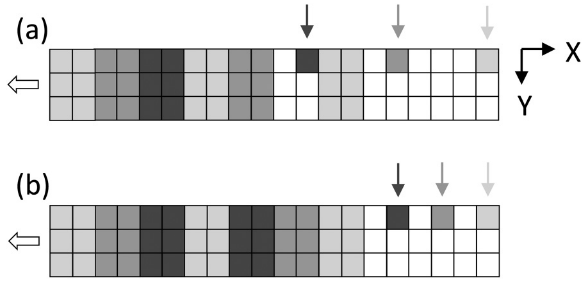

FIG. 9. Distribution of exposed pixels at the end of the first step in a cycle: (a) $I_{bx} = 4$ and (b) $I_{bx} = 2$. $W_p = 2$ and $H_p = 3$ for the pattern in this figure. The coprimes of $H_p = 3$ are 1 and 2. Therefore, 1 and 2 can be allowed as a normalized beam interval, $I_{bx}/W_p = I_{bx}/2$.

C. Beam control

The substrate moves under the 2D array of beams. A cycle is the time duration, expressed in step, required to expose all of N_p pixels in the pattern.

The order of turning on beams: The first beam in each row of beams starts to expose the pixels in the pattern first. Let i be the beam index in a row, where $i = 0, 1, \ldots, H_p - 1$. That is, the index for the first beam is 0. Then, the i-th beam is turned on (i.e., starts to expose pixels) in the j-th cycle where j is the smallest integer for which $jN_p \geq iI_{bx}$.

The order of beams exposing pixels: When $W_p = 1$, each beam exposes one pixel in a row in a cycle and the interval between pixels exposed by a beam is N_p. The i-th beam exposes the $(iI_{bx} \bmod N_p)$-th pixel in each interval, where $i = 0, 1, \ldots, N_p - 1$. When $W_p > 1$, the i-th beam exposes the $(iI_{bx} \bmod N_p)$-th W_p pixels in each interval, where $i = 0, 1, \ldots, H_p - 1$ (note that $H_p = N_p/W_p$). Note that each beam exposes pixels in more than one row in general ($H_p > 1$). Pixels in other rows are exposed following the same order of beams.

D. Beam deflection angle

Given a (final) pattern, pixels in the pattern can be exposed in any order, still being able to achieve a uniform dose distribution. However, in order to minimize the maximum deflection angle of a beam and also the change of deflection angle between steps in each cycle, it would be necessary to expose pixels in the decreasing order of the distance from a beam to pixels where the distance is a relative distance within the pattern.

E. Nonuniform dose distribution

A uniform dose distribution is assumed in this paper. However, it should be clear that a nonuniform dose distribution can be easily realized by selectively turning off certain beams during the exposing process for a uniform dose distribution. Beams to be turned off in each step can be determined by the shape of nonuniform dose distribution. This method may not guarantee the shortest exposing time that is possible by a massively-parallel e-beam system. In another study, methods to minimize the exposing time are being developed for both uniform and nonuniform dose distributions.

V. MINIMIZATION OF ΔD AND LOCALIZATION

In order to minimize the effects of faulty beams, ΔD and the localization of affected pixels need to be minimized. Note that minimizing the localization is to maximize ΔX and ΔY. In this section, this issue of minimization is considered for the multirow writing method.

A. ΔD

The larger the ΔD is, the more likely the corresponding pixel is not developed. Therefore, it is desirable to minimize the maximum possible ΔD. One way is to minimize the number of times a pixel is exposed by a beam. In the multirow writing, a pixel is exposed only once by a beam in each cycle, and, therefore, the dose reduction by a faulty beam is minimal, i.e., d in a cycle. In general, when n_f out of n_c beams exposing a pixel through n_c cycles are faulty (refer to Sec. III), the total dose reduction for the pixel $\Delta D = n_f d$.

B. Horizontal localization (ΔX)

When $W_p = 1$, each beam exposes every N_p-th pixel in a row. Therefore, the distance between the pixels exposed by the same faulty beam is N_p. With $W_p = 1$, the horizontal localization of affected pixels is minimized, i.e., ΔX is maximized to be N_p.

When it is desirable to limit the deflection angle, in particular in the Y dimension, it is necessary to allow $W_p > 1$ so that H_p can be reduced. When $W_p > 1$, each beam exposes W_p consecutive pixels in a row in a cycle, and, therefore, there can be a group of W_p horizontally-adjacent affected pixels, i.e., $\Delta X = 1$. However, it is possible to increase ΔX, i.e., decrease the horizontal localization, by partitioning a pattern with $W_p > 1$ into W_p subpatterns with $W_p = 1$ as illustrated in Fig. 10. Then, the results in Sec. IV can be utilized to determine the beam interval and control considering a subpattern as a pattern. With this partitioning, ΔX is increased to $N_p / W_p = H_p$.

C. Vertical localization (ΔY)

So far, it has been assumed that a pattern consists of H_p consecutive rows, i.e., there is at least a pixel in every row of a pattern. Therefore, it is possible that pixels in a pattern are vertically close, or even adjacent, to each other. In order to reduce this vertical localization of affected pixels, a pattern may be spread vertically by inserting empty rows in the pattern.

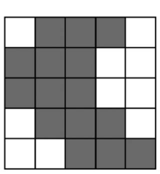

FIG. 10. Pattern with $W_p > 1$ can be partitioned into W_p subpatterns with $W_p = 1$ to reduce the horizontal localization of affected pixels.

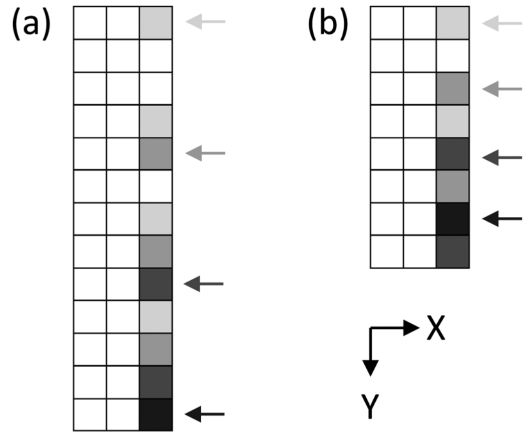

FIG. 11. Pattern can be spread vertically to reduce the vertical localization of affected pixels: (a) $H_p = 4$, $I_{by} = 4$ and (b) $H_p = 2$, $I_{by} = 2$. In the illustration, it is assumed that the pattern consists of H_p consecutive pixels in a column.

Let N_e denote the number of empty rows inserted between pixels in a pattern. Then, the vertical pixel interval in the pattern becomes $N_e + 1$. That is, each beam in a row (of beams) exposes a pixel (or W_p pixels when $W_p > 1$) in every $(N_e + 1)$-th row along the vertical dimension. Therefore, $\Delta Y = N_e + 1$ (refer to Sec. II). N_e pixels between the pixels exposed by a beam are exposed by the beams in other rows. Let I_{by} denote the beam interval in the vertical dimension. One way to ensure a uniform dose distribution without any hole or overlap when inserting N_e empty rows is to meet the following conditions:

$$\begin{aligned} &N_e = H_p - 2 \text{ and } I_{by} = N_e + 2 \quad \text{when} \quad H_p > 2, \\ &N_e = 2 \text{ and } I_{by} = 2 \quad \text{when} \quad H_p = 2. \end{aligned} \tag{2}$$

Examples for $H_p > 2$ and $H_p = 2$ are provided in Figs. 11(a) and 11(b), respectively.

VI. DISCUSSION

In Table I, the multirow writing method is compared with the three cases of single-row writing.

In the multirow and single-row III writing methods, a faulty beam reduces the dose of a pixel least, i.e., by d, in a cycle ($\Delta D^{(1)}$). On the other hand, the single-row I and single-row II writing methods reduce the dose of a pixel significantly more ($n_s d$ and $(n_s/n_g)d$, respectively) when a beam is faulty. Also, the possible dose reduction through multiple cycles ($\Delta D^{(n_f)}$) is smaller in the multirow (and single-row III) writing method than in the single-row I and single-row II writing methods for the same number of faulty beams (n_f). In addition, to cause the same amount of dose reduction as when a pixel is exposed by n_f faulty beams in the single-row I writing method, it has to be exposed by $n_f n_s$ faulty beams in the multirow writing method. However, the probability of $n_f n_s$ beams being faulty out of $n_c n_s$ beams is much lower than that of n_f beams being faulty out of n_c beams. That is, it is very unlikely that $\Delta D^{(n_f)}$ is the same for the two methods.

TABLE. I. Comparison of the single-row and multirow writing methods.

	Single-row I	Single-row II	Single-row III	Multirow[a]
$\Delta D^{(1)}$[b]	$n_s d$	$\frac{n_s}{n_g} d$	d	d
$\Delta D^{(n_f)}$[c]	$n_f n_s d$	$\frac{n_f n_s}{n_g} d$	$n_f d$	$n_f d$
n_c[d]	$\frac{D}{n_s d}$	$\frac{D}{n_s d}$	$\frac{D}{d}$	$\frac{D}{d}$
n_f[e]	$0 \le n_f \le n_c$	$0 \le n_f \le n_g n_c$	$0 \le n_f \le n_c$	$0 \le n_f \le n_c$
ΔX[f]	0, n_s	0, n_s	1	n_s
ΔY[g]	—	—	—	N_e
N_{bx}[h]	$\frac{D}{d}$	$\frac{D}{d}$	$\frac{D}{d}$	$\frac{n_s D}{d}$
N_{by}[i]	L	L	L	$\frac{L}{n_s}$

[a] $W_p = 1$ and $n_s = N_p$.
[b] $\Delta D^{(1)}$ denotes the dose reduction for a pixel due to a faulty beam in one cycle.
[c] $\Delta D^{(n_f)}$ denotes the dose reduction for a pixel due to n_f faulty beams out of n_c beams exposing the pixel through n_c cycles.
[d] n_c denotes the number of cycles needed to achieve the dose D per pixel (the number of beams exposing each pixel).
[e] n_f denotes the number of faulty beams out of those exposing a pixel.
[f] ΔX denotes the minimum horizontal distance between pixels affected by a faulty beam.
[g] ΔY denotes the minimum vertical distance between pixels affected by a faulty beam.
[h] N_{bx} denotes the number of beams required in a row to achieve the dose D per pixel.
[i] N_{by} denotes the number of rows of beams required to expose L rows of pixels in one path.

The horizontal localization (ΔX) of different pixels affected by a faulty beam is the same for the multirow, single-row I, and single-row II writing methods. The single-row III writing method results in the highest level of horizontal localization among different affected pixels, i.e., $\Delta X = 1$, and a large number of consecutive pixels in a row are affected. The multirow writing method has an ability to reduce the vertical localization (i.e., increase ΔY) of the pixels affected by a (faulty) beam. The larger the pattern (the spatial distribution of pixels to be exposed by each beam) is, the more the vertical localization can be reduced.

The number of beams required in each row of the 2D beam array is larger for the multirow writing methods than the other methods, but the number of rows of the beam array is smaller. The total number of beams required to expose a circuit pattern is the same for all the methods. Therefore, the overall performance of the multirow writing method is considered to be better than those of the other methods in terms of the dose reduction due to faulty beams and the localization of affected pixels.

It is worthwhile to point out that, in the case of the multirow writing method, beams need to be deflected in both X and Y directions and the maximum deflection angle can be larger depending on the pattern compared to the other methods. However, since the distance between the deflection lens and the substrate is usually much larger than the deflection distance on the substrate, the deflection angle is very small and, therefore, any effect must be practically negligible.

Also, it should be mentioned that the overlapping or multipass exposure process may be employed in a single-row writing method (also in the multirow writing method) to mitigate the effect of faulty beams, in particular the dose reduction. The degree of overlapping and the number of passes determine the level of mitigation. Let the beam cross-section be a square of size $B \times B$ and the exposing interval be denoted by I_e in both dimensions. It has been implied in this paper that $I_e = B$. When $I_e < B$, each pixel is exposed by multiple beams in an overlapping manner. Assuming that B/I_e is an even integer, each pixel is effectively exposed $n_o = (B/I_e)^2$ times. For the same D, d would be n_o times smaller compared to the case of nonoverlapping exposure process. Therefore, the dose reduction by a faulty beam, $\Delta D^{(1)}$, can be decreased by the factor of n_o.

VII. SUMMARY

In a massively-parallel e-beam system, it is unavoidable that some beams become faulty. In this study, a writing method, referred to as *multirow writing*, which minimizes the negative effects of faulty beams, is designed. By allowing each beam to expose pixels in more than one row in each writing path, the multirow writing method reduces the number of times a pixel is exposed by a faulty beam and spreads affected pixels spatially. Therefore, the possible dose reduction at an affected pixel and the localization of affected pixels are minimized. The main contributions of the work reported in this paper are to develop the general procedures to realize the multirow writing method and derive the conditions required for the realization. The realization procedures provide a way to implement various patterns and control the localization level of affected pixels. Also, the multirow writing method is compared with the single-row writing methods in terms of the dose reduction and localization of affected pixels.

The multirow writing method performs better than the single-row writing methods, achieving a smaller dose reduction (compared to the single-row I and II writing methods) and a lower localization of affected pixels (compared to the single-row III writing method). It needs to be pointed out that, unlike the multipass writing strategy, the multirow writing enables these improvements without having to expose each writing path more than once.

The system model employed in this study is similar to the two massively-parallel e-beam systems, eMET (Ref. 3) and MBM-1000,[6] recently developed. Also, in another study, it has been shown through an extensive simulation that the multirow writing method can achieve higher qualities of pattern transfer than the single-row writing methods. Therefore, this writing method has a good potential to be utilized in massively-parallel e-beam systems, by itself or in conjunction with other methods and the general procedures of realizing the method may be referred to in designing a writing method for future systems with similar operational modes.

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