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GEOMETRIC ANALYSIS OF SOFT ERRORS AND OXIDE DAMAGE PRODUCED BY HEAVY COSMIC RAYS AND ALPHA PARTICLES

John N. Bradford
Rome Air Development Center
Deputy for Electronic Technology
Hanscom AFB MA 01731

Abstract

The interaction of fast heavy ions and alpha particles with microelectronic cells is examined. An analytic expression for the event rate due to the cosmic flux is derived based on the track length distribution in rectangular volumes. Both transient (soft errors) and permanent (oxide damage) effects are considered. The multiple hit consequences of the LSI/VLSI cells lying in a common plane are developed.

Introduction

The continued reduction in size of elements in microelectronics, the matrix array of such devices in a planar field (chip), the size of the finite volume of radiation effect surrounding an ion track and the variation in possible source distribution all require geometrical analysis when one attempts the description of heavy ion and alpha particle radiation effects in VLSI/LSI. These relationships have confronted other investigators in such widely ranging fields as Radiation Biology and Nuclear Reactor Theory. The basic mathematics formalism has been developed in the field of Geometric Probability. This work draws upon those areas of endeavor for application in VLSI electronic circuitry.

Dose Distribution Around an Ion Track

The column of ionization which a fast heavy ion leaves in its wake has been described previously.[1,2] The central core contains doses of $\sim 5\times10^{6}$ Rad(Si) for protons and $\sim 5\times10^{9}$ Rad(Si) for Fe^{56}.

Although bound by Poisson statistics in the energy loss via production of delta rays, the track can be viewed as a cylinder in the material of interest whose radius is approximately 1 μ and within which the dose falls off from the center as r^{-2}. For this work it is the size of the cylinder in relation to the size of electronic devices, as displayed in Fig. 1, and the energy deposited therein that is of interest.

Track Length Distribution in 3-Dimensions

The distribution of lengths of ion tracks from an isotropic source which is generated as the ions transit a convex volume in straight lines is the same mathematical distribution that one derives for the case of random lines intersecting a convex volume. The formulation from Geometric Probability which describes this case was developed by Coleman.[3] Kellerer[4] subsequently derived the formalism for right cylinders of arbitrary cross section and that

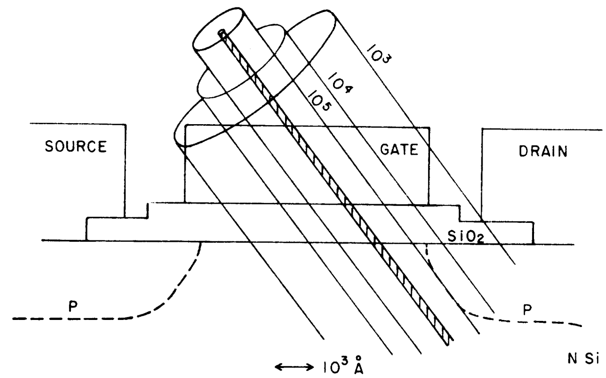

Fig. 1. The dose profile which surrounds a heavy ion track is shown in the perspective of a VLSI device. Circles are labeled in Rads(Si). Dose radii and channel length are to scale. Other dimensions are approximate.

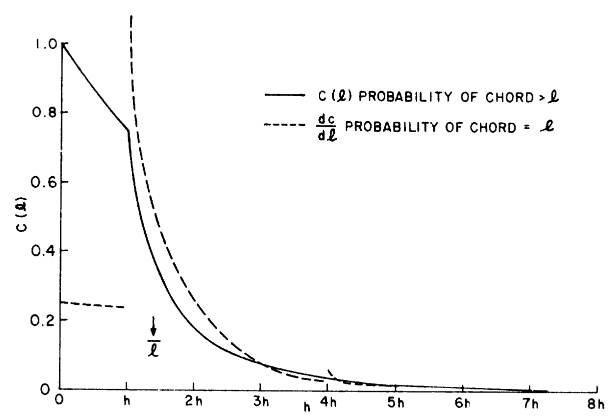

Fig. 2. The sum and differential probabilities for chord length distribution in a rectangular volume of dimensions hx4hx6h.

formalism has been used by Bradford[5] to treat the case of a rectangular parallelpiped. The solution for the probability distributions of track lengths (chord lengths) is shown in Fig. 2 for a rectangular volume hx4hx6h.

The integral distribution (probability that a track length be < ℓ) is obtained from[5]

$$C(\ell) = \frac{8(a+b)}{\pi S}\int_{d}^{1}\frac{h t^{2}}{(1-t^{2})^{\frac{1}{2}}}\, F(\ell t) + t\, F^{*}(\ell t)\,dt \quad . \tag{1}$$

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where

t is the 2-dimensional chord length and

$$d = 0 \qquad t \le h$$

$$d = \sqrt{1 - h^2/\ell^2} \qquad t > h$$

and where $F(\ell\, t)$ and $F^*(\ell\, t)$ are 2-dimensional distritions derived from a rectangle axb and h is the height of the rectangular volume ($h < a < b$). We can compute an event rate using $C(\ell)$ by noting that any convex body immersed in a random flux, φ particles/$cm^2 \cdot$sec, will experience $\varphi S/4$ transits/sec where S is the total surface area.

$C(\ell)$ is taken as the probability of

$$\ell > \ell_{threshold} = \frac{\Delta E_{threshold}}{LET \cdot \rho}$$

where LET is Linear Energy Transfer and $LET \cdot \rho = \frac{dE}{dx}$ and the event rate is given by

$$n = \frac{S}{4} \int_{x_0}^{x_{max}} \Phi(x) C(\frac{\Delta E}{\rho x}) dx \text{ per sec per device} \qquad (2)$$

assuming 100% efficiency for the process (i.e., charge collection), $\Phi(x)$ is the LET flux in particles/$cm^2 \cdot sec \cdot MeV \cdot cm^2/gm$, x is LET in MeV cm^2/gm and $\varphi = \int \Phi(x) dx$.

$C(\ell)$ is a reasonably complex function and the event rate integral usually requires machine solution.

Equation (2) is reducible to a simple form by taking the following definitions for the integrand:

For the cosmic ray ($6 \le Z \le 26$) LET flux

$$\Phi(x) = \Phi(x_0)(\frac{x_0}{x})^P = 4\pi(4x10^{-3})(\frac{10^3}{x})^{3.8} \text{ particles}/M^2 \cdot sec \cdot MeV\ cm^2/gm$$

with the values for x_0, $\Phi(x_0)$, P taken from Ref. 11, and taking

$$C(\ell) = C(h)(\frac{h}{\ell})^{2.2} = .75\,(\frac{h\rho x}{\Delta E})^{2.2}$$

as a reasonable approximation for chord lengths greater than h in rectangular volumes of elongation greater than 2. (See Ref. 5).

$$x_0 = \frac{\Delta E}{\rho \ell_{max}} \pm 10^3 \text{ MeV } cm^2/gm$$

$$x_{max} = \frac{\Delta E}{\rho \ell_{min}} \pm 7x10^3 \text{ MeV } cm^2/gm$$

are the limits in the integral of Eq. (2), where the numbers are examples for the 4K RAM of Ref. 6. Insertion of the above and carrying out the integration yields

$$n = 7.5x10^{-7}\, NS\, (\frac{h\rho}{\Delta E})^{2.2}[(x_{mx})^{-.6}]$$

$$= 7.5x10^{-7} NS\, (\frac{h\rho}{\Delta E})^{2.2}[(\frac{\rho\ell_{mx}}{\Delta E})^{.6} - (\frac{\rho\ell_{min}}{\Delta E})^{.6}]$$

$$= 7.5x10^{-7} NS\, (\frac{h\rho}{\Delta E})^{2.8}[(\frac{\ell_{mx}}{h})^{.6} - 1]$$

$$= 7.5x10^{-7} NS\, (\frac{h\rho}{\Delta E})^{2.8}[(\frac{10\Delta E}{h\rho})^{.6} - 1]$$

$$\text{(events/year} \cdot \text{N devices)} \qquad (3)$$

since $\ell_{min} = h$ in this approximation, ℓ_{max} is the major diagonal of the volume. This result is valid for cosmic ray flux with LET > 10^3 MeV cm^2/gm, ($6 \le Z \le 26$) where

S = surface area of device sensitive volume in μ^2
h = device sensitive volume minimum dimension (presumably depletion depth) in μ.
E = switching energy in MeV
N = number of devices
ρ = density in gm/cm^3

Insertion of values from Pickel and Blandford[6] (e.g., ΔE = 5.6 MeV, h = 3.5 μ, N = 96,000, S = 833 μ^2) yields n = 406. According to them, however, the memories are only "on" half the time so that one would expect 203 events/year.

This is a result in reasonably close agreement with the more approximate calculation of Pickel and Blandford. However, the agreement is fortuitous. Consider for example that the minimum LET specified in that work was $4.86x10^{+3}$ MeV cm^2/gm whereas the geometry (major diagonal) permits 10^3 MeV cm^2/gm for the minimum, as used in this work.

Perhaps a more important feature of the approximation is that it exposes the sensitivities of the event rate to the pertinent parameters. The product NS tends to remain constant with increasing device density and represents the intercept area to the cosmic flux. Hence, to decrease the event rate one needs to scale the minimum dimension (presumably depletion depth) faster than the threshold energy. This represents the chief design criterion for avoidance of soft errors: large ΔE, small h.

Permanent Damage (Oxide) vs Soft Error

The requirement for soft error production is basically an ion track of sufficient length to deposit the needed energy in the collection volume. It is for that reason that the track length distributions in Fig. 2 are important. The longer track lengths can only come from ions with large angles of incidence to the plane of the device as shown in Fig. 3. This response to angle of incidence has been measured experimentally.[12,13] Thus, establishing a threshold energy for the device error is equivalent to setting an angular limit on the angles of incidence for each LET group.

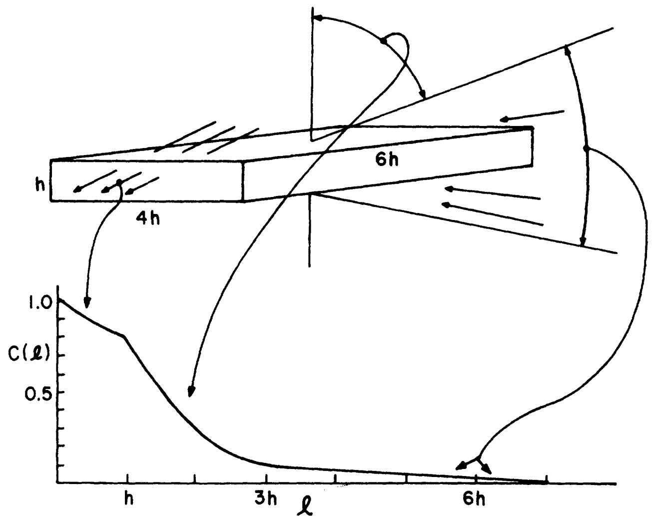

Fig. 3. The relationship between angles of incidence and contribution to various portions of the sum distribution of chord lengths is shown.

In the case of an ion transecting an oxide layer two damage mechanisms are probable: (1) The normal threshold voltage shifts associated with oxide charge trapping and (2) A permanent effect associated with the non-uniform dose around an ion track and its size relative to the device. No threshold energy deposition requirement exists for the latter, hence, all ions of all LET rates are considered. In that situation it is the size comparison between the device area and the track cross section that is important. These are shown for a conceptual interaction between a cosmic ray and a VLSI MOS transistor in Fig. 1. Since the effect of the highly ionized region which surrounds the ray path on an oxide is at present not well known, no attempt at an event rate prediction is undertaken here.

Equation (3) above can be used to some value, however, in the average dose case subject to the same validity restrictions. If ΔE is set as the energy required to achieve some average dose in the oxide, then

$$\Delta E(\text{MeV}) = 1.6\text{x}10^8 \; D(\text{rads}) \; V(\text{cm}^3). \tag{4}$$

For example, an oxide layer of .1 μm thickness and an area of LSI scale, $14\text{x}21\ \mu\text{m}^2$, for 10^3 rads

ΔE = 4.7 MeV and from Eq. (3)

n = .65 events/year$\cdot 10^5$ devices

Thus it is with exceedingly small probability that one would see an LSI size gate oxide receive a dose of 10^3 rads or greater from the single pass of a cosmic ray.

If the area is shrunk to VLSI dimension with $V = .1\text{x}1\text{x}1\,\mu\text{m}^3$, then for 10^4 rads or greater

ΔE = .16 MeV and from Eq. (3)

n = 3 events/year. 10^5 devices.

For 10^3 rads or greater

$$\Delta E = .016 \text{ MeV but } \frac{\Delta E}{\ell_{min}\rho} \doteq 660 \text{ MeV cm}^2/\text{gm}$$

which violates the validity criterion, LET $\geq 10^3$. Therefore, one would have to resort to the formal solution of Eq. 2 for evaluation. Many events can be anticipated as a result of this low LET requirement.

It remains of course to determine what fraction of these events lead to sufficient threshold voltage shifts to disable them. With the general decrease in hardness associated with increased device density, the magnitude of this effect is not certain.

Discrete Source Distribution

One of the sources of ion interaction in microelectronic cells arises from ppm contamination of glass and ceramic packaging by U/Th.[7] The resulting alpha decay leads to soft errors in RAM cells. It is noted here the impact of a possible situation: suppose the U/Th is distributed not in a homogeneous fashion but in discrete particulate clumps, as shown in Fig. 4.

To determine the total number of cells which have ν traversals one must integrate the probability distribution over all the cells which lie within the range of the decay products. For α particles of range, R, emanating from a clump of activity, A, situated a microns above the plane containing N memory cells in a RAM of area D we have

$n = k/r^3$ $\quad k = \dfrac{AS^2\,at}{4\pi}$ where n is the average number of traversals

$P(\nu) = \dfrac{e^{-k/r^3}(k/r^3)^\nu}{\nu\,!}$ for the Poisson distribution

$N_r = (\frac{N}{D})\pi(r^2 - a^2)$ for the device areal density

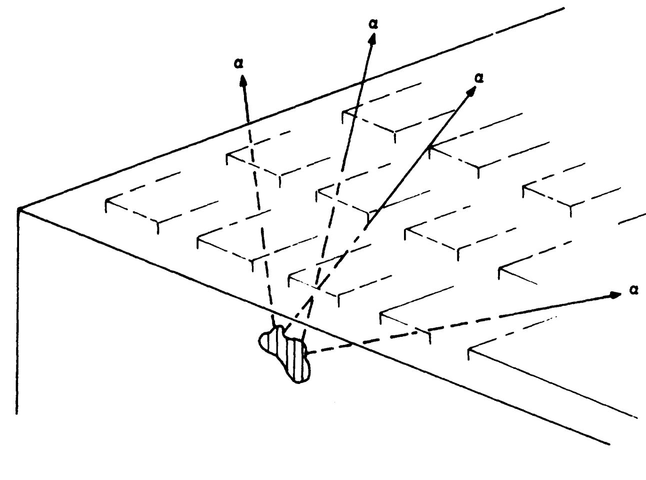

Fig. 4. Clumped activity distribution in relation to VLSI array.

The linear density of cells is $dN_r/dr = 2rN_R$ where

$$N_R = \frac{N}{D}\pi .$$

The total number of cells hit by ν traversals is then

$$N(\nu) = \int_a^R P(\nu)\frac{dN_r}{dr}\,dr \tag{6}$$

which by insertion of the above becomes

$$N(\nu) = \int_{a/R}^{1} \frac{e^{-c/x^3}}{\nu!}\, c^{\nu} x^{-3\nu+1}\, 2R^2 N_R dx$$

where $x = r/R$ and $c = k/R^3$ and finally

$$N(\nu) = \frac{2R^2 N_R c^{\nu}}{\nu!}\int_{a/R}^{1} e^{-c/x^3} x^{-3\nu+1} dx \tag{7}$$

The integral is easily evaluated numerically and an example has been computed for the following conditions:

$At = 10^4$ decays
$R = 25\ \mu$
$a = 5\ \mu$
$N_R = \pi\cdot 10^6/16\text{x}10^6 = \pi/16$ (VLSI)

The results are shown in Fig. 5. An activity·time of 10^4 for U^{238} in one year requires $A = N\lambda$

$N \doteq 5\text{x}10^{13}$ atoms.

The above mode of analysis has been used by Kellerer to predict the cell survival rate in lung cells exposed to particulate Pu_2O_5. In that case, as here, more than one hit may be required for cell death. In the present case, repeated traversals of the memory cell oxide may lead to cell disablement. The formalism thus allows a prediction of the rate of those occurrences.

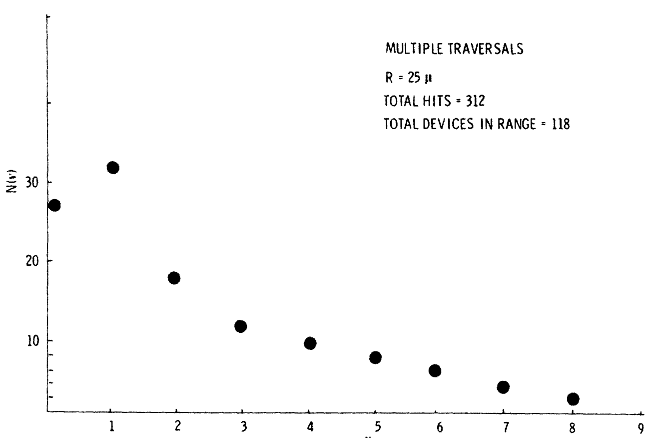

Fig. 5. The multiple traversal distribution for α particles from U^{238}. Range is 25 μ and area density on chip is 1 cell/4 μ^2 (VLSI).

Multiple Hit Probabilities

The event rates calculated in Eq. (2) assumed total independence of cells and hence no multiple hits (e.g., one ion hitting more than one cell). If the cells are contained in an array, it is clear that those tracks of large incidence angle have a probability of hitting more than one cell as shown in Fig. 6 for the case of a 4K RAM. This section attempts to determine the magnitude of that multiple hit process.

Assume N devices in an array, with mean separation distance, q on a chip of area A. The device thickness (presumably the depletion depth) is h. The general problem is intractable in 3 dimensions and indeed has been treated successfully in 2 dimensions only for the case where the elements (devices) are circular.[9, 10] One can achieve a solution,

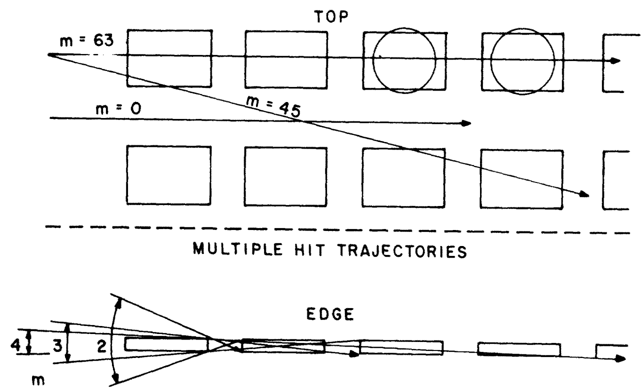

Fig. 6. The relationship between angular incidence and multiplicity of hits is shown in the scale of a 4K RAM.

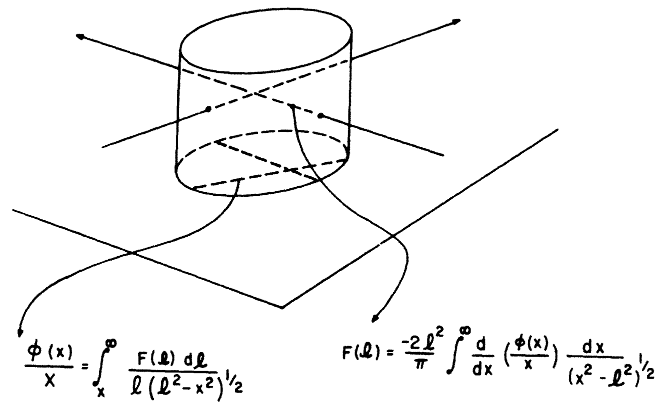

Fig. 7. Relationships between 3-dimensional distribution of tracks and their projection onto a plane.

however, as follows. The procedure is to take the 3 dimensional chord length distribution and project it into 2 dimensions as indicated in Fig. 7. The device areas are then approximated by circles of diameter 2R.

From Kendall and Moran[9] Geometric Probability the number of random transects of circles of diameter 2R contained in area A for a chord of length L is

$$n = 4L\,RN/A \tag{8}$$

where N is the number of circles, A is large area (chip).

The formalism to project the chord distribution in 3 dimensions into 2 dimensions is

$$\frac{\varphi(x)}{x} = \int_x^\infty \frac{F(\ell)}{\ell(\ell^2 - x^2)^{\frac{1}{2}}}\, d\ell\,. \tag{9}$$

$F(\ell)$ is the 3 d distribution and we use the infinite plane slab approximation

$$F(\ell) = 2h^2/\ell^3$$

leading to

$$\frac{\varphi(x)}{x} = \int_x^\infty \frac{2h^2}{\ell^4(\ell^2 - x^2)^{\frac{1}{2}}}\, d\ell \tag{10}$$

where $\varphi(x)$ is the chord distribution in the plane. Integration yields

$$\varphi(x) = \frac{4h^2}{3x^3}\,. \tag{11}$$

Integration of this distribution times Eq. (8) yields the total hits from the incident flux due to chords of length > q, where q is mean separation distance, $\sim(\sqrt{A/N})$, (see Appendix 1).

$$n = \frac{\Phi A}{4}\int_q^\infty \frac{4h^2}{3x^3}(4xRN/A)dx \tag{12}$$

$$= \frac{\Phi A}{4}\,\frac{h^2}{q}\left(\frac{16}{3}RN/A\right) \tag{13}$$

The total number of ions incident on the chip with chord length ≥ q given by

$$\frac{\Phi A}{4}\,\frac{h^2}{q^2}\,.$$

Hence the multiple hit factor is the ratio

$$m = \frac{\frac{\Phi A}{4}\,\frac{h^2}{q}\left(\frac{16}{3}RN/A\right)}{\frac{\Phi A}{4}\,\frac{h^2}{q^2}} = \left(\frac{16}{3}RN/A\right)q \tag{14}$$

For the 4K RAM

$$m = \frac{16\text{x}8.5\text{x}4000\text{x}33}{3\text{x}4\text{x}10^6} = 1.4$$

For a 10^6 RAM in VLSI on the same chip

$$m = \frac{16\text{x}1\text{x}10^6\text{x}2}{3\text{x}4\text{x}10^6} = 2.6$$

Finally, note this multiplier is not simply related to the event rate prediction formalism unless the events are due to only long chord lengths. To establish a correspondence to the event rate in general one must know the distribution function for chord lengths in the devices which results from this restricted set of incidence angles. That distribution is unknown at this time.

Summary

The reduction in size of microelectronic devices has lead to a revised view of relevant radiation effects. Geometrical, statistical and distributional analysis is now required for accurate description of radiation effects in these devices. Much of the required analysis technique can be borrowed from radio biological literature. This work has emphasized the geometrical factors pertinent to accurate representation of radiation effects in small devices subjected to fast heavy ion flux.

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Appendix 1

Derivation of Mean Distance of Separation

From pages 37-38 of Ref. 9 assume the objects (projections of the sensitive volume onto a plane) are randomly distributed in the plane. Then let λA be the number of points in area A (λ is density). The number of objects in area of radius r is $\pi\lambda r^2$. Consider the distance to the nearest neighbor to be r_1, then the set of values r_1 is distributed according to

$$2\pi\lambda r_1 dr_1 e^{-\lambda\pi r_1^2}$$

The mean value for nearest neighbor distance is then

$$\bar{r} = \int_0^\infty 2\pi\lambda r^2 e^{-\lambda\pi r^2} dr \quad .$$

In our case $\lambda = N/A$ the device density on a chip of area A.

Define $x = \lambda\pi r^2$, then

$$\bar{r} = \frac{1}{(\pi\lambda)^{\frac{1}{2}}} \int_0^\infty x^{\frac{1}{2}} e^{-x} dx \quad .$$

$$\int_0^\infty x^{\frac{1}{2}} e^{-nx} = \frac{1}{2n}\sqrt{\pi/n}$$

is a standard form so that for $n = 1$

$$\bar{r} = \frac{1}{\sqrt{\pi\lambda}}\left(\frac{\sqrt{\pi}}{2}\right) = \frac{1}{2}\sqrt{\frac{1}{\lambda}} = \tfrac{1}{2}\sqrt{A/N}$$

LSI and VLSI devices are not randomly distributed, however, and for a given chip, all nearest neighbor distances are presumably the same. We want the minimum distance of separation rather than the mean, hence, for a matrix array of $\sqrt{N}$ devices on a side of length $\sqrt{A}$, the separation distance is $\sqrt{A/N}$.