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ORIGINAL PAPER

Angle control requirements and solutions for enabling high aspect ratio structures

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Abstract

Modern device structures for flash memory applications can require the use of low energy ion implantation through high aspect ratio structures. SK Hynix and Axcelis jointly investigated the implant parameters related to contact resistance (Rc) variation for this application. The conventional beam quality metrics of mean beam angle, beam angle spread, beam height and beam width were insufficient to describe the Rc variation.

Axcelis proposed a model to fit the Rc with angle distribution. To complete the investigation a trace data analysis of raw data while angle measurements were collected on the existing processing tools at the SK Hynix Fab was executed which confirmed the proposed model. To enable lower variation in contact resistance at higher productivity Axcelis has developed hardware and software optimizations to minimize the angle distributions at higher beam currents. The solutions have been production proven at SK Hynix and this paper proposes standardization of the term Angle Distribution to describe the standard deviation of angles in the ion beam at a measurement location with the qualifiers of Vertical and Horizontal to describe the components of the angle distribution in each of these directions.

Introduction

SK Hynix flash memory production utilizes several low energy, high dose processes into high aspect ratio devices. Over time the device aspect ratio has increased significantly and is now $\geq$ 40:1. As the aspect ratio has increased so has tool-to-tool, lot-to-lot and wafer-to-wafer Rc variation. This variation which was as high as 13.46% (standard deviation) could not be well modeled with any signals on the implanter (a ribbon beam ion implanter hence referred to as tool "Type B"). Early in the Purion Dragon development this high aspect ratio process was tested and similar Rc variation to the "Type B" tool was observed but the technical team identified a potential correlation between Rc and vertical angle distribution (hence referred to as VAD).

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Hypothesis

The hypothesis for the observed correlation between VAD and Rc is the loss of ions into device structure sidewalls. Although the exact implant condition and the sidewall composition of this device are confidential an approximate proportion of ions backscattered from the sidewall was estimated using a simple *Stopping and Range of Ions in Matter* (SRIM) simulation of 3 keV Boron ions impinging on a SiO_2 target at a variety of angles ranging from 0.1° to 25°. To simplify the model the implant is presumed to be in quad mode and the device structure is assumed to be symmetrical in the (*x*-) and (*y*-) directions such that the impact to dose at the contact can be estimated from one angle distribution parameter.

The distribution of angles within the beam is assumed to be Gaussian and all current with an angle that reaches the bottom of the contact is assumed to contribute to the Rc (less backscattered ions) while current with an angle that strike the sidewall is assumed to contribute to the Rc after multiplication by an attenuation factor based on the SRIM modeled scattering at the sidewall incidence angle. For the device structure in question this model predicts that the Rc repeatability would be < 2% target if the upper limit on standard deviation of the angles was set to 1.5° assuming a uniform

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distribution of wafer-to-wafer angle distributions down to 0°. This limit is specific to the 3 keV B+ implantation into the modeled structure with the modeled sidewall composition since scattering behavior of the incoming ion changes with the species, target, and energy. Obtaining such small angle distributions also becomes more challenging with higher mass or lower energy. Insufficient neutralization from the plasma electron flood would also result in worse angle distribution performance due to space charge repulsion and from potential charge-up of the device sidewalls during implant.

Angle parameterizations

The most common definitions of beam angles are mean and parallelism (or spread) of angles in (*x*-) and (*y*-). The mean is simply the average of one or more angle measurement across the wafer area across a given direction while the parallelism or spread give information about the range of these measurements. These metrics describe variations in the average incidence angle across multiple locations but do not quantify the variation in the angles of the ions striking a single location on the wafer.

Purion implanters report Vertical and Horizontal Angle Distribution (VAD and HAD). These are estimates of the standard deviation of angles within the beam at each measurement location in each direction. A similar metric has also been referred to as "IAD" on a medium current ion implanter which has been described in reference to Rs variation due to channeling behavior at much higher energy and much lower beam current [1]. This parameter has been reported since the Purion H introduction in 2014 and has been largely unconstrained for low energy, high dose applications where the acceptance angle of the channel is wide compared to angle distributions [2].

To calculate VAD or HAD, each angle measurement can be thought of as a density profile where the measurement is the quantity of beam current at a given physical position or angle. The observed density profile is a convolution of two signals: (1) the angle distribution of the beam at the measurement location and (2) the physical acceptance of the measurement device. Using Gaussian approximations of the measured current density profile, the physical acceptance of the device and the beam allows for an estimate of the ion beam's angle distribution by trivial deconvolution of variances to arrive at an estimate of the standard deviation of angles in the ion beam.

Test of hypothesis

It has been reported that within-wafer angle spread may have a strong impact on some device parameters and that these sensitivities should be mitigated by tighter angle spread control and the use of Quad Mode implants [3]. The literature also hypothesizes sensitivity to angle distribution [3], however, the "Type "B" implanter does report local angle distribution, so an estimate of VAD was made from the data collected during angle measurement. If angle distribution (standard deviation referenced as: σ_b) is not reported it may be estimated from the profile of current versus angle:

$$Centroid\left(u_{\emptyset}\right) = \frac{\sum_{i=1}^{n} Ib_i \times \emptyset_i}{\sum_{i=1}^{n} Ib_i} \quad (1)$$

$$Density\ Profile\ Variance\ \left(\sigma^2\right) = \frac{\sum_{i=1}^{n} Ib_i \times \left(\emptyset_i - \mu_{\emptyset}\right)^2}{\sum_{i=0}^{n} Ib_i} \quad (2)$$

$$Angle\ Distribution\ \left(\sigma_b\right) = \sqrt{\sigma^2 - \sigma_m^2} \quad (3)$$

$\sigma_m = Variance\ from\ Measurement\ Acceptance$, $Ib_i = Beam\ Current\ at\ index\ i, \emptyset_i = Angle\ at\ index\ i.$

The angle and current data from the "Type B" tools was processed through the equations above and confirmed the hypotheses that the device Rc is better fit by VAD than any parameter available at the time from the "Type B" tool. Figure 1 shows the strong relationship between the estimated Tool Type "B" VAD and the device Rc.

Experimental optimization

The approach to optimizing the VAD to control Rc variation implemented by Axcelis involved three paths: Software Limitation, Recipe Setup/Beam Tuning Guidelines and Automatic Tuning and Hardware Geometry Optimization.

Recipe limits were added to control HAD and VAD to augment the preexisting limits constraining angle mean and spread. These limits are applied during AutoTune allowing the control system to automatically adjust, recover and proceed if the measured angle distribution exceeds the limit. These limits are also applied as a pre-implant interlock and each angle distribution measurement is available to the fab Host monitoring system as are the recipe limits.

Experimentation in the Axcelis factory was executed to define a beam tuning/recipe setup guideline, built automatic tuning functions and to optimize the hardware design. This testing employed a scripted search of tuning parameter variants for each of a series of different modifications to the injection optics. Figure 2 illustrates the results of several experiments covering a wide range of tuning solutions from five arc slit tests.

The analysis of the results proved that angle distributions (*x*- and *y*-) are best tuned as far upstream in the beamline as possible. Figure 3a illustrates a 2D surface of VAD by

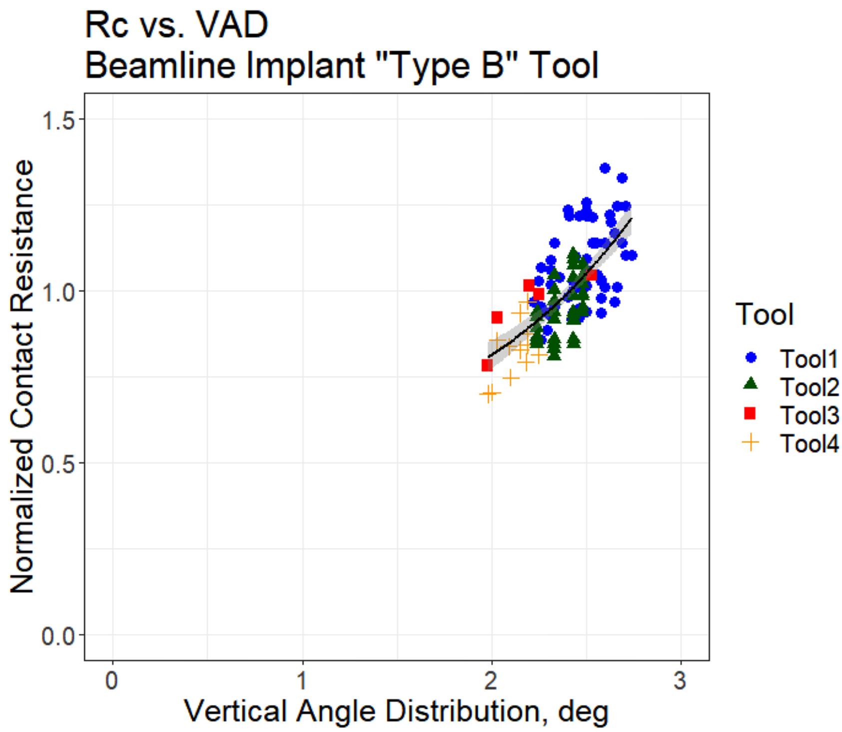

Fig. 1 Using the Eqs. (1)–(3) described in this paper the VAD was estimated from the center vertical angle faraday on each of 4 "Type B" implanters. Despite using only the center VAD, the potential for VAD drift from measurement to implant or physical wear of the measurmeent device (changing the real value of the σ_m in Eq. 3) a correlation od 0.685 was found between the estimated VAD and the Rc. The decision to use only the center faraday was made because at the time of the experiment the Purion Dragon had not yet introduced the upgrade kit to measure the vertical angle and VAD at both edges of the wafer in addition to the center measurement so a direct comparison between the tools was desired

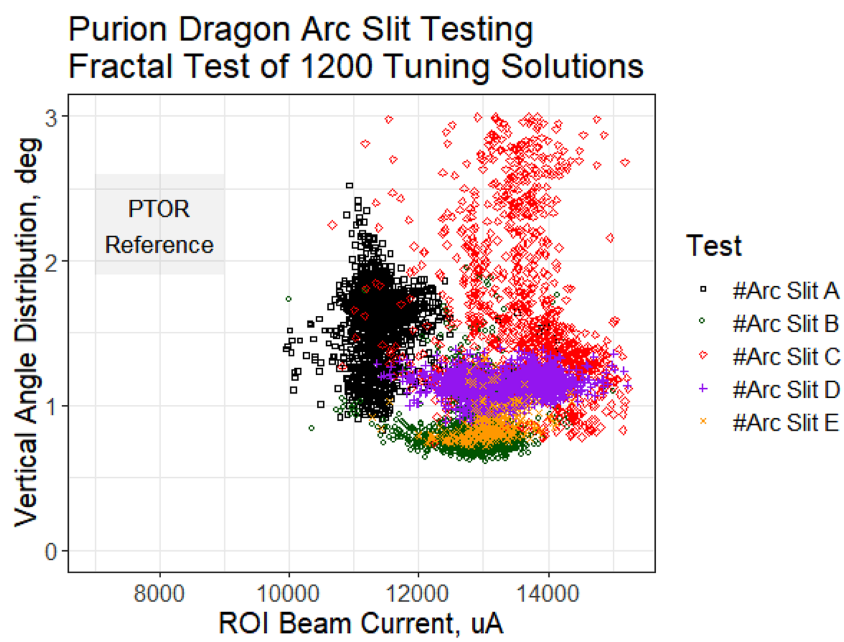

Fig. 2 B^+ 3 keV ROI beam current is the scanned beam current in the wafer area. Tuning and hardware optimization are constrained to accept only solutions meeting several beam quality criteria: uniformity < 1%, VAD < 1°, HAD < VAD, ROI beam current between 12 and 14 mA with the Extraction Power Supply Voltage and Current held constant to within 0.2% and 2%, respectively

quad magnet tuning. When a new recipe is setup, a simplex routine is used to approach the minimum of this surface. Throughout the aging of the source the preferred method is to keep the quad magnet currents at their history values and tune only the gap between the arc slit and extraction electrode to find the minimum angle distribution as shown in Fig. 3b.

Each time a new optical hardware design is modified it is tested through the same fractal script allowing the features which maximized the proportion of the tuning space which is simultaneously compliant to all process limits to survive as opposed to optimizing for a champion value in one or more parameter. This optimization path was selected

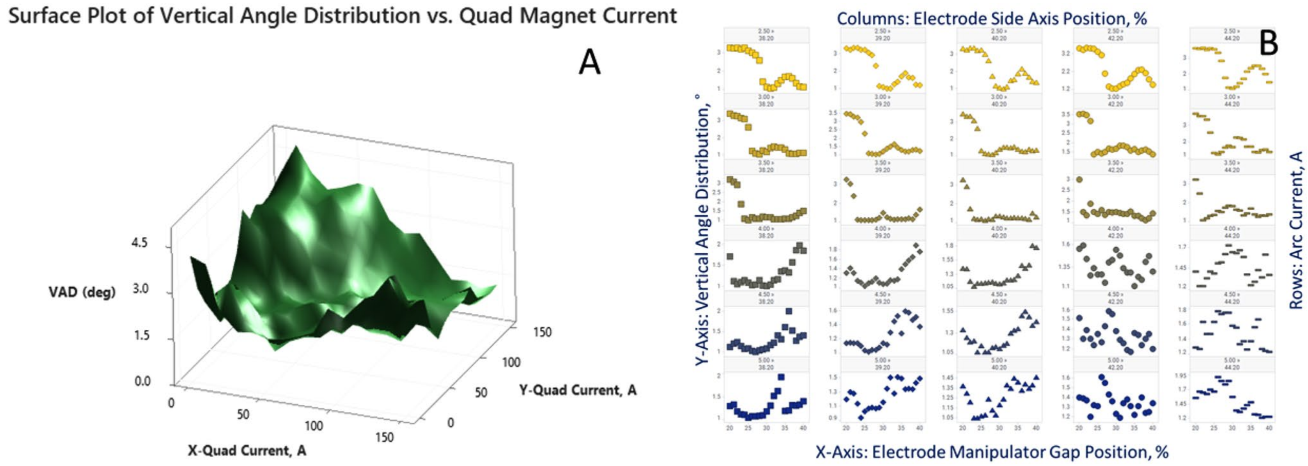

Fig. 3 **a** Grid search for VAD by quad currents: during automatic tuning a simplex algorithm is used to rapidly find the minima of this surface without searching the entire grid. Although the simplex method is faster than a full search the two parameter symplex is still slower than a single parameter tuning step and the minima is relatively constant. The perfered tuning method is to apply the simplex method only when a new recipe condition is created or as a recovery method if automatic tuning by the Gap Axis fails. **b** The preferred method is to keep all of the downstream elements including the quad magnet currents fixed at history values and use the gap between the arc slit and the extraction suppression electrode to find the minimum angle distribution.The gap was selected for this purpose because the optimum gap posistion for minimum VAD shifts with tuning solution and with age of the source but for the majority of combinations of other tuning parameters the VAD recipe limit may be met simple adjustment of the gap position: illustrated for combinations of Arc Current and Electrode Side Axis position

to maximize the capability of the machine to meet the device requirements in high volume mass production.

Results

Following the initial study, a Purion Dragon tool was placed in a production fab to focus on low energy boron, high aspect ratio processes. Over several generations of device evolution and increasing aspect ratio, the target VAD has reduced from unconstrained, to targeting first less than 1.5° and now on a higher aspect ratio device 0.99°. Over 20 months in production with > 66,000 wafers implanted with the less angle sensitive “Recipe 1” and > 210,000 wafers implanted with the more angle sensitive “Recipe 2”. The Purion Dragon has demonstrated a mean VAD of 1.27° with a maximum of 1.66° on the less sensitive “Recipe 1” and a mean VAD of 0.861° with a maximum of 1.24° on the more sensitive “Recipe 2”. Figure 4a illustrates the production machine VAD and HAD history for the two processes. Although no significant correlations were observed between HAD and Rc the sensitivity must exist if the underlying VAD hypothesis is true. For the 3 keV boron recipe on the “Type B” tool the beam width is approximately seven times the height and thus the current density in the horizontal direction is substantially lower than in the vertical direction. Given the low horizontal current density, the “Type B” tool is anticipated to have HAD values comparable to those shown from the Purion Dragon in Fig. 4b which are below the threshold at which variation in Rc is observed from VAD. Figure 4b shows the ion beam scanning across each of three vertical angle faradays from the multi-VBA kit which was not yet installed on the machine in Fig. 4a. The data are collected at 250 kHz while the beam scans at 81 Hz. This makes angle and angle distribution calculable both as the average across the wafer and at each position within the beam.

Conclusions

Evolution of flash memory architecture is resulting in the manufacturing process requiring the simultaneous use of increasingly high aspect ratio structures and lower energy ion implants. The simple angle measurements of mean and spread are no longer sufficient to describe the ion beam properties which directly impact the Rc repeatability of devices using high aspect ratio structures. It is imperative that all ion implanter manufacturers expand their angle metrology offerings to include multiple angle distribution measurements across the wafer area to improve Rc repeatability for these applications.

Purion high current products report a local distribution of angles at multiple locations across the wafer by deconvolution of measurement device acceptance from angle profile data. Variation in this metric has been proven to be predictive of variation in Rc on a SK Hynix high aspect ratio device implanted on another vendor’s high current implanter by analysis of trace data collected during angle

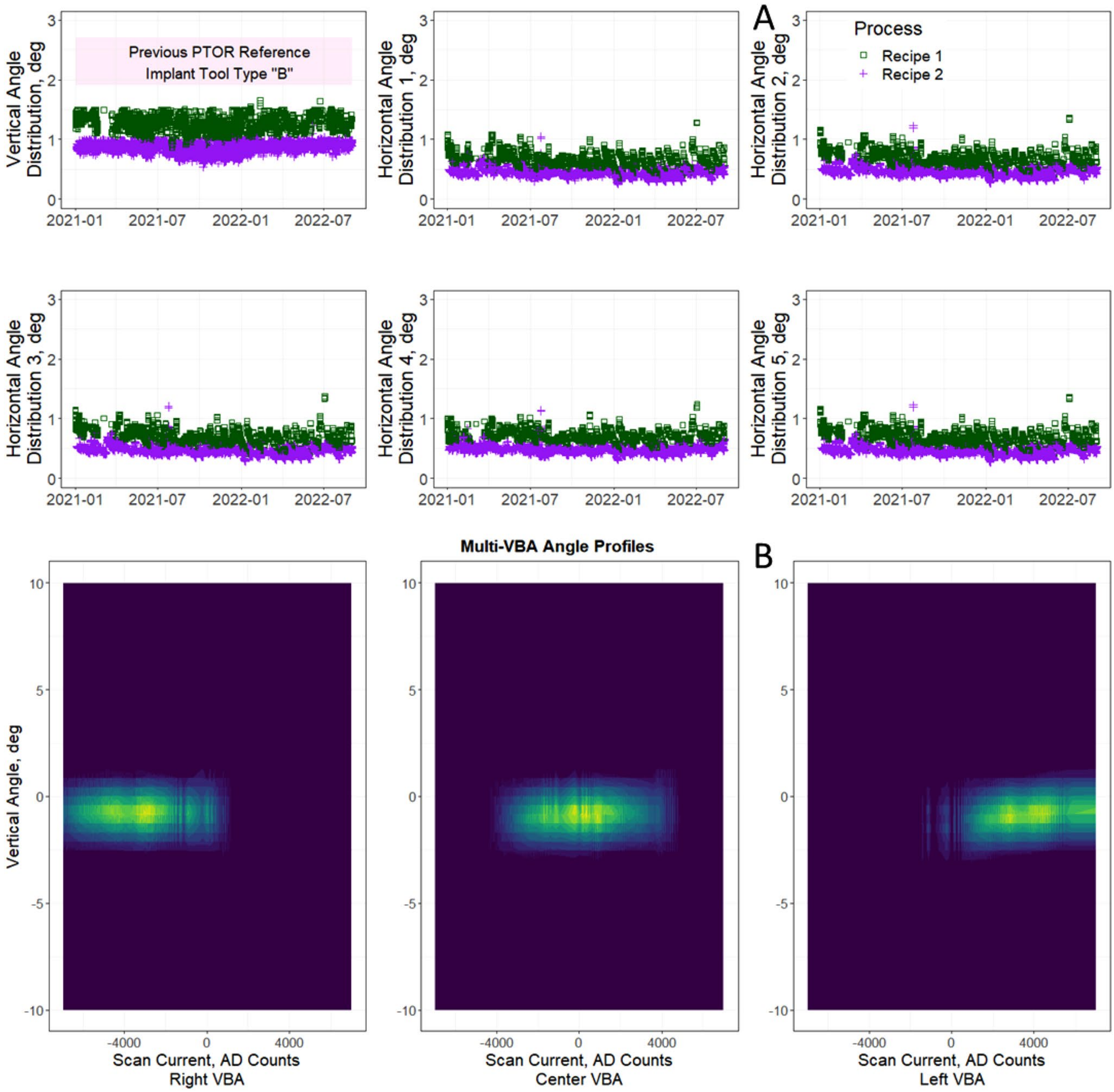

Fig. 4 **a** Production history of VAD for two high aspect ratio device recipes from a Purion Dragon at a SK Hynix production fab. The majority of lots were constrained by 1.5° and 1.0° limits, respectively, with limits removed for several lots for confirmation of the Rc sensitivity to angle distribution. The VAD measurement is collected at wafer center while the five HAD measurements are collected at evenly spaced locations across the wafer area. **b** Due to the scanned spot beam archetecture it is possible to see the angle and angle distribution at all locations within the spot beam at each vertical angle measurement device by reading the beam current from the measurement device at substantially higher frequency (250 kHz measurement) than the scanning frequency of the beam (81 Hz scanning) and synchronizing the beam current measurement to the horizontal scan of the beam. This is illustrated for the vertical angle measurement locations on a factory tool because the Multi-VBA kit was not yet installed on the production tool from (**a**)

measurement. By application of recipe limits, optimization of automatic beam tuning and design of injection optics the Purion Dragon has demonstrated the ability to deliver sustainably lower angle distribution at higher beam current than the "Type B" implanter over 20 months in high volume production. This result is counter to previous literature suggesting that spot beam implanters should be more susceptible to higher angle distribution than broad, unscanned beam systems such as the "Type B" tool [4]. We do not contradict the theory that angle distribution is sensitive to current density, however, when beam height is tuned without consideration for VAD the tendency is to produce larger, more variable VAD which translates directly to device parameter variation.

We propose that the act of measurement and control of the angle distribution is necessary to deliver acceptable angle distributions regardless of machine architecture and thus propose standardization of the term Angle Distribution to describe the standard deviation of an angle profile after deconvolution for measurement device acceptance and that this parameter should be reported for all angle measurements in both horizontal and vertical direction on all modern ion implanter equipment.

Additional discussion

There are several factors which are critical to the anticipated device results when implanting into small contacts of which the angle distribution in the ion beam is only one. As shown by Tamura et al. there are also impacts to dose and damage arising from the size of the contact relative to the lateral straggle of the ion beam even at perfect incidence angle with a theoretical 0° divergence beam [5]. Especially when the implant is executed in "quad mode" which implants the total dose in four equal segments offset by 90° rotations of the platen, this straggle effect is relatively insensitive to implant angle and was thus excluded from this analysis of the Rc variation on the "Type B" implanter.

We recognize that not all contacts are squares or circles as viewed from the incoming beam. In the case of a rectangular open area the sensitivity of the Rc to angle distribution can obviously be reduced by setting the implant twist to align the smaller dimension of the opening with the less divergent axis of the beam. It is also possible with the scanned spot beam to fully understand the angle present at each position in the spot and pattern the flux profile to achieve not uniform flux but uniform "within critical angle" flux to theoretically eliminate Rc sensitivity to angle distribution. This method was not pursued in this study because the approach is only theoretically possible if every open region of the mask has the same aspect ratio which was not true in this case.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request. In the cases where data may reveal proprietary details about either SK Hynix device properties or Axcelis implanter design results may be normalized and features not discussed in this study may be redacted to avoid back-calculation of such proprietary details.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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