Present address: Department of Physics, Flinder's University, South Australia, Australia 5001.

I. INTRODUCTION

In the semiconductor industry, argon ion beams are often used in sputtering, ion-assisted chemical etching, and ion-assisted deposition. As such, the effects of argon bombardment of silicon have drawn considerable research interests, although few data are available for bombardment below 1 keV. Recently, Al-Bayati et al. reported a thorough study of crystal damage by argon bombardment at 60-510 eV as a function of fluence (1-30X10^15/cm^2) and substrate temperature (17-300 °C). Medium energy ion scattering spectroscopy was used to measure the defect distributions with a depth resolution of 3 Å. In summary, amorphization of the near-surface region was observed with a fluence about 5X10^15/cm^2 for the room-temperature bombardments. The analysis, however, did not provide any experimental data on argon incorporation.

Related to this, detailed data on argon incorporation in tungsten in the bombardment energy range 40-5000 eV were measured by Kornelsen with fluences less than 1X10^19/cm^2. He showed that the incorporation reached saturation near 1X10^16/cm^2 and that the incorporation probability at 100 eV was less than 0.001 even before saturation occurred. Such a complete set of data, to our understanding, has not been measured on silicon. Comas and Wolicki published probably the earliest data on argon incorporation in silicon by ion bombardment in the energy range of 20-2000 eV. The experiment was, however, done with very high fluences (1-2X10^19/cm^2). A drastic increase in incorporation probability versus bombardment energy was shown in the energy range 20-100 eV. For example, for a fluence of 2X10^15/cm^2, the incorporation probability as 4X10^{-6} at 20 eV but rose to about 1X10^{-3} at 100 eV. The published data also showed that when the fluence changed only from 1X10^19/cm^2 to 2X10^19/cm^2, the incorporation probability increased by almost a factor of 10. This enormous fluence dependence casts some doubt on the accuracy of the measurements.

For argon bombardment of silicon at 1 keV, Filius et al. found that argon incorporation reached a quasiosaturation at about 1X10^16/cm^2 but increased again above 5X10^17/cm^2. The incorporation probability was always about unity before the saturation occurred. The quasiosaturation was partially attributed to self-sputtering and the increased incorporation at higher fluences was attributed to argon bubble formation.

The purpose of the present article is to provide further experimental information on argon trapped in silicon during low energy ion bombardment. In this study, the concentration of argon incorporated by ion bombardment of silicon was measured in the fluence range 10^{14}-10^{19}/cm^2 at 100 eV so that the data can be compared with the 1 keV data published by Filius et al. In addition, the ion energy effects were investigated by repeating the bombardment experiments at 15 and 20 eV. Further, the thermal desorption rate of the trapped argon was measured at 25, 250, and 500 °C in order to facilitate the elucidation of the trapping mechanism. Polar-angle dependent x-ray photoelectron spectroscopy (XPS) and Rutherford backscattering spectroscopy (RBS) were used for characterizing argon incorporation.

II. EXPERIMENT

The ion bombardment experiments were performed in a mass-separated low energy ion beam system which has been described elsewhere. Briefly, positive ions extracted...
from an ion source are accelerated to a beam voltage of 3 kV and are focused to a Wien filter for mass separation. The ion beam is then refocused into a deceleration lens unit in the target chamber, and is decelerated there before it bombards the target. For the characterization of the low energy ion beam, a quadrupole mass spectrometer equipped with a cylindrical ion energy analyzer, the VG SXP300H model, is housed along the beam axis in the target chamber. In addition, a movable Faraday cup with a 1.3 mm entrance aperture is used to measure the beam current density at the target and to map the beam current profile. A large Faraday cup can also be placed in the target position to measure the total beam current. In the present study, during ion bombardment, the pressure was $4 \times 10^{-7}$ Pa in the target chamber. The total argon ion beam current at the target was about 3 μA and the beam was purposely defocused to give a near-flat current distribution within 2 mm from the beam center. Although computer controlled beam scanning could be performed with the system, the defocusing was used to simplify the experiment and shorten the bombardment time for a given fluence. The mass resolution of the system was about 40 and the energy spread was estimated to be about 1 eV.

The substrate was p-Si (100) which was cleaned with a HF solution immediately before loading into the ion beam system. The bombarded sample was transferred, in a vacuum of $1 \times 10^{-6}$ Pa, to a Surface Science Instrument SSX-100 x-ray photoelectron spectrometer for compositional analysis. Measurements were performed at different polar angles and with an x-ray spot size of 300 μm. Mapping of the argon lateral distribution near the bombardment center was carried out first on each sample with a pixel size of 1 mm to verify the location of the bombardment center. Argon and silicon concentrations were estimated using their $2p$ photoemission intensities and using the form factors derived by Scofield.

Some polar-angle dependent measurements were also performed with a VG CLAM-2 spectrometer which is linked with the low energy ion beam system. The analysis area was about 0.6 mm in diameter. The acceptance angle was about 2° as compared to 15° for the SSX-100 spectrometer. Desorption of the incorporated argon was also studied in this spectrometer. The sample holding mechanism allows the maintenance of the sample at different temperatures during the XPS measurements.

After the XPS analysis, samples were transferred via air to the General Ionex Tandetron system at the University of Western Ontario for RBS measurements. In these measurements, a 1 MeV He$^+$ beam was used. The He$^+$ beam size was 2 mm in diameter and the location of the beam within the argon irradiated area was facilitated by a video camera and precalibrated beam marker.

### III. RESULTS

The incorporation of argon in the target as a result of argon ion bombardment was confirmed by both XPS and RBS. For example, Fig. 1 shows the Ar $2p$ XPS spectrum of a sample receiving a fluence of $2 \times 10^{12}$/cm$^2$ at 100 eV at room temperature. With reference to the valence band edge of the semiconductor, the binding energy of the argon $2p_{3/2}$ level was determined to be at 241.2 eV. The spin-orbit splitting and branching ratio were 2.18 and 2.0 eV, respectively. This is in good accord with the spectra reported from argon implanted in graphite which showed a $2p_{3/2}$ level at 241.5 eV and a spin-orbit splitting of 2.2 eV (Ref. 9).

The spectrum in Fig. 1 was taken using the SSX-100 spectrometer with a polar angle of 0°. When the polar angle of detection was altered, the XPS derived argon concentration also changed. The dependence is summarized in Table I. The angle dependent data collected with the CLAM-2 spectrometer were also included. In XPS measurements, the polar angle dependence arises from the loss of photoelectron intensity under a spectral peak as a result of inelastic scattering of the photoelectrons when they travel from the emission site to the surface. The photoemission intensity measured at a polar angle $\theta$ is given by

$$I_{\text{detected}} = (I_{\text{emitted}}) \exp[-(t/cos \theta)/\lambda],$$

TABLE I. Argon atomic concentrations derived by XPS data collected at different polar angles with the bombardment energy at 100 eV and fluence at $2 \times 10^{12}$/cm$^2$.

<table>
<thead>
<tr>
<th>Polar angle of detection (deg)</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>37</th>
<th>42</th>
<th>55</th>
<th>60</th>
<th>71</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective sampling depth (Å)</td>
<td>25</td>
<td>24</td>
<td>22</td>
<td>20</td>
<td>19</td>
<td>14</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Atomic concentration of argon (at. %) with the SSX-100 spectrometer</td>
<td>0.013</td>
<td>0.014</td>
<td>0.015</td>
<td>0.016</td>
<td>0.019</td>
<td>0.016</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>Atomic concentration of argon (at. %) with the CLAM-2 spectrometer</td>
<td>0.013</td>
<td>0.013</td>
<td>0.015</td>
<td>0.016</td>
<td>0.019</td>
<td>0.016</td>
<td>0.015</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 1. The Ar $2p$ spectrum of argon incorporated in silicon (binding energy referenced to the valence band maximum of the semiconductor).
where $I_{\text{emitted}}$ is the photoemission intensity at the emission site which is located at a distance $t$ below the surface. The parameter $I_{\text{emitted}}$ is proportional to the concentration of the chemical element emitting the corresponding photoelectrons. As such, Eq. (1) shows that the XPS atomic concentration, which is proportional to $I_{\text{detected}}$ depends on the depth distribution of the chemical element and the experimental sampling depth. The latter is governed by $\lambda$, the inelastic mean free path of electrons in a solid, which depends on both the electron kinetic energy and the solid. Using the inelastic scattering model published by Tanuma et al.,\textsuperscript{10} we found that the respective inelastic mean free paths of the silicon $2p$ and argon $2p$ photoelectrons in silicon under our analysis conditions are 26 and 24 Å, respectively. In order to simplify the analysis of the spectral data, the inelastic mean free paths for the silicon and argon photoelectrons are assumed to be 25 Å in this study. Rearrangement of Eq. (1) yields

$$
t = (\lambda \cos \theta) \ln \left( \frac{I_{\text{emitted}}}{I_{\text{detected}}} \right). \tag{2}
$$

If the effective sampling depth $t_{\text{effective}}$ is defined as the depth of the emission location where 63% of the photoemission does not undergo inelastic scattering, then

$$
t_{\text{effective}} = \lambda \cos \theta. \tag{3}
$$

With the above definition and assumption, one can see that at a polar angle of 0°, the top 25 Å surface layer is sampled, and that the sampling depth decreases to 8 Å when the polar angle increases to 71°.

The polar angle dependent data from both the SSX-100 and CLAM-2 spectrometers (Table I) show that when the effective sampling depth increases from 14 to 25 Å, the XPS derived argon concentration decreases. This dependence indicates a drop of the actual argon concentration in the sample beyond a depth of about 14 Å. Similarly, the decrease of the XPS derived argon concentration when the sampling depth was changed from 14 to 8 Å indicates that there was a surface depletion of argon. This argon distribution, which peaks at 10–20 Å and drops both towards the surface and the bulk, agrees well with the expectation that argon ions with an incident energy of 100 eV will go subsurface but cannot penetrate too deeply into the bulk and that argon atoms stopped closer to the surface will have a higher probability of escape to the surface and subsequent desorption.

An analysis of the polar angle dependent XPS data was also carried out by assuming a Gaussian distribution of argon in silicon. The three parameters for defining such a function are the peak position ($R_0$), the full width at half-maximum ($w$) of the peak, and the peak concentration ($C_0$). In implantation terminology, the first two parameters are related to the projected range and the straggling, respectively, whereas the last parameter is determined by the fluence. In the present analysis, relative polar angle dependent XPS data ($I_{\text{det}}$) with a Gaussian argon distribution are calculated with the following equations:

$$
I_{\text{det}}(\theta, R_0, w) = \int_0^\infty \exp \left( - \left( \frac{x-R_0}{1.2w} \right)^2 \right) dx,
$$

$$
I_{\text{det}}(\theta, R_0, w) = I_{\text{det}}(\theta, R_0, w) / I_{\text{det}}(71°, R_0, w),
$$

The optimization of $R_0$ and $w$ is performed by minimizing the variance $\kappa^2$ between the experimental and calculated XPS derived argon concentrations

$$
\kappa^2 = \sum \left[ \frac{(I_{\text{experimental}}(\theta_i) - I_{\text{optimized}}(\theta_i))}{I_{\text{optimized}}(\theta_i)} \right]^2.
$$

This data analysis when applied to the results collected for the sample bombarded at 100 eV to a fluence of 2 × 10\textsuperscript{17} cm\textsuperscript{-2} (Table I) gave an optimal set of $R_0$ and $w$ at 14 and 8 Å. In comparison, computer simulations using the transport of ions in matter (TRIM) program\textsuperscript{11} (with an assumed displacement energy of 15 eV) gave $R_0$ and $w$ at 9 and 6 Å, respectively. The integration of the argon distribution gives the total amount of argon in the bombarded silicon per unit area which was 3 × 10\textsuperscript{14} cm\textsuperscript{-2} for this sample. The incorporation probability was therefore about 0.0015 for such a bombardment.

The above bombardment experiment and analysis were repeated with ion energies of 15 and 20 eV at a fluence of 2 × 10\textsuperscript{17} cm\textsuperscript{-2}. The respective $R_0$-$w$ sets were 4–6 Å and 8–9 Å, and incorporation probabilities were 0.0004 and 0.0007.

The RBS spectrum collected from the sample bombarded at 20 eV is shown in Fig. 2. The RBS data gave an argon content of 1.4 × 10\textsuperscript{14} cm\textsuperscript{-2} with an estimated error less than 10%. The measurement gave an incorporation probability of 0.0007, which is in good agreement with the XPS results. It is, however, worth pointing out that in this study, the XPS analysis was usually performed immediately after each bombardment without any air exposure of the sample, whereas RBS was carried out after the XPS analysis with sample transfer via air. In a parallel study, we found by in situ XPS that bombarded samples stored in ultrahigh vacuum at room temperature for several days did

\begin{figure}
\centering
\includegraphics[width=\textwidth]{rutherford_backscattering_spectrum}
\caption{Rutherford backscattering spectrum of Si (100) bombarded by argon at 20 eV to a fluence of 2 × 10\textsuperscript{17} cm\textsuperscript{-2}.}
\end{figure}
not show any change in their argon contents and distributions. However, a one-day air exposure of the samples bombarded with 20 eV Ar⁺ caused about 20% decrease of argon. As such, the RBS measurements likely yielded a slightly underestimated argon incorporation. The interpretation of the effects of silicon oxidation to the incorporated argon will require more systematic investigation.

In the study of the fluence effects, we found that for the three energies used here, increasing the fluence initially increased the total amount of incorporated argon. A quasisaturation was reached at about $1 \times 10^{19}$/cm$^2$. More argon, however, could be incorporated when the fluence was higher than $1 \times 10^{19}$/cm$^2$. The most complete set of these fluence dependent data was collected at 100 eV, which is summarized in Fig. 3. The fluence dependent data collected by Filius et al. for argon bombardment of Si(111) at 1 keV are also included.

In order to learn more about the argon incorporation mechanism, we measured the residual argon concentration as a function of time at three different temperatures (25, 250, and 500 °C). The sample was bombarded with 100 eV Ar⁺ to a fluence of $1 \times 10^{19}$/cm$^2$. XPS data were collected at a polar angle of 0°, which is the most bulk sensitive configuration. The results of this set of experiments are summarized in Fig. 4. As mentioned earlier, the incorporated argon was stable at room temperature for many hours. Heating the sample at 250 °C caused an exponential decrease of the argon concentration, but after a 25% reduction the change in concentration became very slow. The decrease, however, was resumed by heating the sample at 500 °C.

IV. DISCUSSION

A. Distributions of argon

As mentioned earlier, Al-Bayati et al. have previously determined the density of displaced silicon atoms by medium energy ion scattering with H⁺ which provides a very high depth resolution of 3 Å. The scattering conditions, however, did not allow the separation of the scattered intensity corresponding to the incorporated argon atoms from that of the silicon atoms in the near surface region. The authors resorted to calculating the implant distribution by the IMPETUS codes with the assumption of total retention of argon. With this methodology, they reported that the displaced silicon atoms, at a bombardment energy of 110 eV and a bombardment temperature of 200 °C, were about $4.5 \times 10^{15}$/cm$^2$ and $7.3 \times 10^{15}$/cm$^2$ for a fluence of 1 and $10 \times 10^{15}$/cm$^2$, respectively. The rather low incorporation probabilities shown in our present study imply that the previous authors have overestimated the retained argon concentrations, and that their backscattered signals near the sample surface were almost entirely due to silicon atoms displaced from their lattice sites.

This previous energy dependent damage analysis also showed that for a fluence of $1 \times 10^{19}$/cm$^2$, the damage depth was found to be 20 Å for argon bombardment of Si (100) at 60 eV at room temperature, 26 Å at 110 eV, 32 Å at 210 eV, and 47 Å at 510 eV (Ref. 3). Hence, the damage depth for bombardment at 100 eV should be about 25 Å. Because bombardment induced defects arise from cascade collisions, the defect distribution should be slightly deeper than the distribution of the incoming projectile. Since our data collected for bombardment at 100 eV show a projected range of 14 Å and a straggling of 8 Å, the penetration depth of argon is thus about 20 Å which agrees reasonably well with this previous damage analysis. In comparison, the range data from TRIM ($R_0$ at 9 Å and $w$ at 8 Å) are slightly lower than ours.

B. Argon trapping mechanism

Our data showed that even at a bombardment energy of 15 eV, argon penetrated into the silicon target with a small but measurable trapping probability. The trapping of argon is intriguing because the chemical affinity between argon and silicon is very small. In fact, like the interatomic potentials for many inert gas–metal pairs which have been quite extensively studied, that for Ar–Si is most probably repulsive in nature. The weak binding is also shown by the fact that while most atoms have a few electron volts of surface binding energy on silicon, that for argon is only about 0.02 eV (Ref. 14). However, it is well-known that substitutional inert gas atoms are quite strongly trapped in many metal lattices. The binding of inert gas atoms
in solid is mainly governed by the local potential wells in the solid, such as those at the interstitial and vacancy sites. For example, the dissociation temperature for a helium-vacancy pair in Mo is about 1170 K (the dissociation energy is about 3.8 eV). Accordingly, it is not unreasonable to assume that argon in silicon is also initially trapped either as an interstitial impurity or as an argon-defect complex.

Although a considerable amount of reliable data has been published on inert gas trapping (mostly on helium) in metals, little information on the inert-gas-silicon system is available. van Wieringen and Warmoltz showed in 1956 that while helium permeates through silicon at 967–1207°C, permeation of argon under the same conditions was not observed. A conclusion was drawn then that interstitial helium diffusion is the main mechanism and the activation energy is about 1.7 eV. The lack of argon permeation thus suggests that the activation energy for interstitial argon migration in silicon may be quite high. In comparison, interstitial helium and argon diffuse readily in metals like Mo and both of them have a migration energy of only about 0.3 eV (Ref. 18). As such, while argon is not strongly trapped in the interstitial sites in metals like Mo, interstitial argon may be stable in silicon.

Recently Filius et al. studied the thermal desorption of argon incorporated in silicon by bombardment at 1 keV with a fluence range of 4.8X10^15–1.6X10^19/cm^2 and found that at low fluences, although desorption started at about 300°C, most of the incorporated argon desorbed at about 600°C with a desorption temperature window of less than 50°C. At higher fluences, several desorption peaks were observed at higher temperatures, in addition to the peak at 600°C. For example, at a fluence of 8X10^18/cm^2, peaks were found at about 750, 950, and 1100°C. These authors proposed that ion bombardment at room temperature gives atomically dispersed argon and argon bubbles, and that the dispersed argon is desorbed during recrystallization of the silicon lattice at 600°C, whereas argon bubbles desorbed at higher temperatures.

In the study of argon trapping at fluorences higher than 1X10^17/cm^2, Sawyer et al. showed by transmission electron microscopy that Si (100) which had been bombarded by 1 keV Ar^+ to about 2X10^18/cm^2 and then annealed to 1050°C contained voids filled with argon with an average diameter of 50 Å. To our understanding, this provides the most direct evidence of argon bubble formation in silicon. No other structural defects such as dislocations were found in the sample, which indicates that argon bubbles are more thermally stable than other extended defects in silicon. However, these authors showed that the samples bombarded at room temperature both with and without annealing at 350°C had no argon bubbles. Since all our samples were treated at temperatures not higher than 500°C, it is plausible that argon bubble formation is not a main argon trapping mechanism in our study (with the definition that argon bubbles are argon clusters with an average diameter larger than 10 Å which can be readily observed by transmission electron microscopy).

The desorption data collected in the present study indicates that a substantial amount of argon incorporated in silicon via ion bombardment at room temperature is released at or below 250°C. Although a clear picture about argon trapping and release mechanisms can only be drawn with more systematic data, the existing data indicate that while argon cannot permeate through silicon even at 1000°C when the silicon has a low defect density, the migration and release of argon takes place at or below 250°C in the presence of native defects. Hence, argon migration and trapping must be critically influenced by the migration of native defects. If interstitial argon indeed has a rather high binding energy in silicon, the argon-defect interactions in silicon is very much different from those in metals like Mo. In the latter case, interstitial argon is very mobile while defects like vacancies diffuse only at 500 K (Ref. 18). Hence, any argon atoms released from one trapping site will diffuse either to another defect site for retrapping or to the surface of the solid for desorption. In silicon, previous studies of silicon defects showed that interstitials are mobile at all temperatures, and vacancies become mobile around 170°C (Ref. 21), and dislocations dissociate efficiently at about 300°C (Ref. 22). It is plausible that the argon release observed in the present study is initiated by the dissociation of divacancies and subsequent migration of vacancies. Such a postulation can be further extended to argue that each argon atom trapped in silicon due to room temperature bombardment has already been visited by some point defects generated in the cascade collision volume of the bombardment event which introduced that particular argon atom or visited by those generated by subsequently arrived argon. As such, the argon incorporation observed in the present study is unlikely to be contributed by the presence of interstitial argon. Instead, the presence of argon-vacancy complexes seems to be a more appropriate source. It is known that for the argon-molybdenium system, while interstitial argon migrates readily at room temperature and Mo vacancies migrate at about 500 K, the release of argon from the argon-divacancy and -trivacancy complexes requires a temperature higher than 800 K and that from the argon-vacancy complex a temperature higher than 1000 K.

Since Baba et al. showed recently that the different chemical potentials of xenon in different metals are reflected in a varying xenon photoelectron binding energy, we have measured the argon 2p_3/2 binding energy (related to the silicon valence band maximum by recording the argon and silicon spectra at each run) as a function of fluorences and annealing conditions. Hitherto, no systematic difference larger than 0.1 eV has been observed. Hence, XPS binding energy measurements do not seem to be a sensitive technique in characterizing the trapping centers in the samples prepared in this study. Nevertheless, the dependence of the argon concentration on fluorences (Fig. 3) and on annealing temperatures (Fig. 4) clearly show the presence of multiple trapping centers for the argon retention.

The argon incorporation probabilities measured in this study decreased significantly as the bombardment energy was reduced. This energy dependence can be understood...
by the fact that argon trapping requires the subsurface penetration of the incident argon. This is clearly shown\textsuperscript{17} by the lack of argon permeation in silicon even at 1000°C. Furthermore, the probability of argon sticking on the top of the first silicon atomic layer must be practically zero at room temperature (argon has a surface binding energy of 0.02 eV, see Ref. 14). Hence, when the bombardment energy approaches a typical thermal energy level (less than 1 eV), 100\% reflection and zero incorporation is expected. However, since argon is heavier than silicon, direct back-scattering under the present normal incident condition is unlikely and therefore will not contribute much to the reflection of argon at low bombardment energies. But even when the bombardment energy is high enough for the argon to go subsurface, the average penetration depth is only about 10 Å at a bombardment energy of 15-20 eV. The incident energy in the rather small collision volume may enhance the migration of the penetrated argon at least for a short period of time. Since its location is so close to the surface, this may provide an argon release mechanism which drives the incorporation probability down as the bombardment energy is reduced. In addition, the strain effect and defect formation at the first few atomic layers of a solid are expected to be quite different from the bulk of the solid. This difference may also contribute to the energy dependence of the incorporation probability.

The quasiasaturation of argon incorporation has previously been explained by a gas-sputtering mechanism. Our understanding is that each argon arrival creates a collision cascade and some mobile defects, and that the release of a previously trapped argon atom can happen because of cascade collision or of defect interactions. Obviously the argon release by this mechanism will only be important when the argon concentration has reached a certain level that a considerable probability exists for a trapped argon being present in the cascade collision volume or in the range of defect migration induced by subsequent argon arrivals.

The above discussion clearly shows that there are many unsettled issues about inert gas trapping in silicon, the understanding of which will require some further careful analyses. To illustrate this future development, we would like to note that recently van Veen\textsuperscript{15} presented some thermal helium desorption spectrometric data on silicon. Although a detailed mechanistic picture of helium and argon trapping in silicon was not given, we believe that such an approach, like its success in generating some basic understanding of inert gas trapping in metal, is very much applicable to the silicon case. We also believe that an investigation of the presence and fate of interstitial inert gas atoms in silicon by ion channeling will also be very useful.

\section{V. CONCLUSIONS}

In the bombardment energy range 15-100 eV, argon incorporates in silicon with a probability much less than unity. The release of the incorporated argon is believed to be assisted by the migration of vacancies which are generated from the dissociation of vacancy clusters. The combination of our data and those published on 1000 eV bombardment consistently shows that in the bombardment energy range 15-1000 eV, argon incorporation probabilities decrease with decreasing energies.

\textsuperscript{2}See, for example, Ion Beam Assisted Film Growth, edited by T. Itoh (Elsevier, Amsterdam, 1989).
\textsuperscript{13}See for example, W. D. Wilson, Radiat. Eff. 78, 11 (1983).
\textsuperscript{17}A. van Wijriagen and N. Warmolts, Physica 22, 849 (1956).
\textsuperscript{20}See for example, J. Bourgoin and M. Lannoo, Point Defects in Semiconductors II (Springer, Berlin, 1983).