Escape length of ultraviolet induced photoelectrons in alkali iodide and CsBr evaporated films: Measurements and modeling

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The escape length of electrons photoinduced from thin CsI, KI, RbI, NaI, and CsBr evaporated films was measured in the 140–180 nm photon spectral range. Theoretical model predictions of the escape length value are in fair agreement with the experimental results. They vary between 10 and 40 nm, the highest values being for CsI, RbI and CsBr. For CsI, measured and calculated ultraviolet-induced escape length values are consistent with that determined from x-ray photoemission quantum yield data. Post-evaporation annealing of the films had no major impact on the measured electron transport properties. © 1998 American Institute of Physics.

I. INTRODUCTION

Alkali halide films are important elements in modern gas avalanche photon detectors. They are employed as efficient photoconverters in the far ultraviolet (UV) and soft x-ray range. Due to their good electron transport properties, they have been recently proposed as thin protective coatings for alkali-antimonide photocathodes. In parallel to extensive experimental investigations of the photoemissive characteristics of alkali halide films in the UV range, we have developed a theoretical model which can predict the electron transport and emission properties. It is based on theoretically calculated microscopic cross sections of electron–phonon interactions; calculations are performed using a Monte Carlo simulation code. The model was implemented for calculating the quantum efficiency of reflective and semi-transparent CsI photocathodes and photoelectron energy spectra. A fair agreement was reached between predicted and experimental data, although reflection effects at the interface between the photocathode and its substrate were only approximately taken into account.

The validity of the theoretical model, and more especially of its electron transport part, can be probed by comparing the calculated and experimental values of the escape length of electrons photoinduced by UV photons in various alkali halides. The electron escape length, also called electron attenuation length in the literature, is the characteristic length through which the photoemission quantum efficiency is decreased to $e^{-1}$ of its initial value for semi-transparent photocathode thicknesses larger than a few UV photoabsorption lengths. Thus, the photocathodes considered should be thicker than several tens of nm, the UV absorption length in alkali iodides and CsBr being around 10–20 nm. The attenuation length is an intrinsic characteristic of the electron transport in the photocathode material and it has often been used in the frame of x-ray photoemission semi-empirical models, for characterizing x-ray photocathodes.

II. EXPERIMENTAL WORK

A. Methodology

The proposed way for deriving the photoelectron escape length in the considered materials is to measure, in transmission mode, the UV-induced photocurrent as a function of the film thickness. In general, the photoelectrons emitted from a photocathode surface can be measured either in a collection mode or after multiplication. In thin semi-transparent photocathodes, only photoelectrons emitted in the forward direction (i.e., the incident photon direction) are relevant. In such a case, the photocurrent measured at the photocathode, in a collection mode, represents the difference between forward (emitted) and backward (flowing to the substrate) currents. In the transmission mode, the backward photoelectron current...
The alkali halide films are deposited by resistive evaporation maintained with an oil-free turbomolecular pumping unit. The latter are first deposit a thin metallic layer in order to provide a fair compromise from conductivity and transmittivity points of view. After the initial photocurrent measurements were found for a photocathode-to-wire grid distance of 4.6 mm and a CH₄ pressure of 100 Torr. HV values of +2500 V and +2600 V on the wires yielded gas gains of 8000 and 32 000, respectively. The methane pressure, stabilized by the gas pressure controller, appeared to be stable for a few hours, within a 0.3 Torr error domain. The typical error due to picoammeter, voltage and pressure fluctuations was estimated to be around 5% for HV=+2500 V and about 9% for HV=+2600 V.

D. Experimental results

1. Electron escape length measurements

In the experimental apparatus described above, the escape length of UV photoelectrons has been measured in alkali iodide and CsBr films. The spectral upper limit (i.e., 200 nm for CsI and 170–180 for other alkali halides) is determined by the photoemission threshold wavelengths of the considered materials. The experimental procedure was to first deposit a ~50 nm thick alkali halide film on the Cr-coated substrate, to insert CH₄ into the vessel, to stabilize its pressure to the nominal value and to measure the amplified photocurrent as a function of the photon wavelength. The value of the high voltage applied to the wire electrode was +2600 V in the case of NaI and +2500 V for the other materials considered in this work. Since the UV photoabsorption length is typically around 10–20 nm in the considered wavelength range, as already mentioned, the initial 50 nm film ensures that most of the photons interacting with the photocathode are absorbed within the film. Thus, for film thicknesses larger than 50 nm, the photon absorption will be low enough to ensure stability upon minor fluctuations in gas pressure or HV values. On the basis of the theoretical model described below, we have simulated, for a few representative photon energies, the photoemission induced from a 50 nm thick semi-transparent CsI photocathode. The contribution of the backward current was found, for a gain of 5000, to be less than 1% of the total current. Therefore, such gain will ensure a fair proportionality between the multiplied measured current and the initial forward-emitted electron photocurrent. Optimal working conditions for our measurements were found for a photocathode-to-wire grid distance of 4.6 mm and a CH₄ pressure of 100 Torr. HV values of +2500 V and +2600 V on the wires yielded gas gains of 8000 and 32 000, respectively. The methane pressure, stabilized by the gas pressure controller, appeared to be stable for a few hours, within a 0.3 Torr error domain. The typical error due to picoammeter, voltage and pressure fluctuations was estimated to be around 5% for HV=+2500 V and about 9% for HV=+2600 V.

B. Experimental setup

The experimental setup is schematically depicted in Fig. 1. It consists of a high vacuum evaporation chamber that allows for depositing a film of a controlled thickness and for measuring the photocurrent induced by monochromatic UV photons in situ. The vacuum in the vessel (~10⁻⁷ Torr) is maintained with an oil-free turbomolecular pumping unit. The alkali halide films are deposited by resistive evaporation on optically polished CaF₂ substrates. The latter are first coated by a thin metallic layer in order to provide a fair electrical contact since these films are utilized as semi-transparent photocathodes. Cr has been chosen because of its relatively, low resistivity. The substrates have been precoated by 3 nm thick films, providing a fair compromise from conductivity and transmittivity points of view. The UV radiation is provided by a vacuum-operated Jobin Yvon H20 monochromator equipped with a L879-01 Hamamatsu D₂ lamp. It is coupled through a CaF₂ window to the vessel. The monochromator resolution was limited by the slit widths to 4 nm to allow for sufficient output light intensity. CH₄ is continuously flowed into the vessel and its pressure is maintained to a constant value by means of a differential pumping system and gas pressure controller. The UV-photoinduced electrons are collected, after multiplication, by a wire electrode (the wires are 20 µm thick and 1 mm spaced) and measured by a picoammeter grounding the photocathode. The intensity of the UV source is monitored during the experiment by a Hamamatsu R1460 reference photomultiplier tube (PMT) and variations are taken into account.

C. Choice of working conditions

The choice of the working gas multiplication factor (gain) is a relevant issue. It depends on three parameters: the distance, d, between the substrate and the wire electrode, the gas pressure and the high voltage (HV) applied to the wire electrode. The gain has to be high enough to make the backward electron contribution negligible, as explained above, and to provide photocurrent values sufficiently high for reaching acceptable signal-to-noise conditions. However, it should be low enough to ensure stability upon minor fluctuations in gas pressure or HV values. On the basis of the theoretical model described below, we have simulated, for a few representative photon energies, the photoemission induced from a 50 nm thick semi-transparent CsI photocathode. The contribution of the backward current was found, for a gain of 5000, to be less than 1% of the total current. Therefore, such gain will ensure a fair proportionality between the multiplied measured current and the initial forward-emitted electron photocurrent. Optimal working conditions for our measurements were found for a photocathode-to-wire grid distance of 4.6 mm and a CH₄ pressure of 100 Torr. HV values of +2500 V and +2600 V on the wires yielded gas gains of 8000 and 32 000, respectively. The methane pressure, stabilized by the gas pressure controller, appeared to be stable for a few hours, within a 0.3 Torr error domain. The typical error due to picoammeter, voltage and pressure fluctuations was estimated to be around 5% for HV=+2500 V and about 9% for HV=+2600 V.
layer was deposited, permitting further photocurrent measurements in CH$_4$. This procedure was repeated until the film thickness attained 75 nm. The measured currents were corrected for the slight increase of the number of photons absorbed within the film as its thickness grew. This was done on the basis of our experimental data for UV absorption length.$^6$

The influence of the CsI film thickness on the UV light coupling to the film, namely the internal reflection at the substrate–CsI interface, was also considered. The coupling was estimated for CsI films, according to Ref. 18 and using optical constants of CaF$_2$, Cr,$^{20}$ and CsI.$^{19}$ For thicknesses in the 50–75 nm range, the coupling exhibits a very small scatter, always less than 1%. Therefore this effect in CsI films can easily be neglected. Since optical constants are not available for the other materials considered here, it was not possible to evaluate their coupling dependence on film thickness. However we assumed that (similarly to CsI) this correction could be neglected for all the alkali halides considered.

At a given photon wavelength, the electron escape length was deduced from the inverse of the fitted slope of the photocurrent versus the film thickness. The measurements have been repeated two or three times for every alkali halide considered here and the presented data for electron escape length are averaged values. The measured electron escape lengths in CsI, KI, RbI, NaI and CsBr are, respectively, presented in Figs. 2–6. One should note that the escape length values for photoelectrons induced in CsI are in the range of 18–34 nm. They are consistent with the values determined from x-ray yield data by Iyèsaar et al.$^7$ and Fraser,$^9$ 22 nm, and by Henke et al.$^8$ 25 nm. The experimental data for NaI are compatible with Kisiel and Lewowski’s values that are in the range of 7–11 nm, but the KI measured escape lengths are about twice their values. One should also note that the attenuation length data measured in all the considered alkali halide films are of the same order of magnitude and are, in general, in the 10–40 nm range.

2. Post-evaporation thermal treatment

It is known that the photoemission quantum efficiency of thick (500 nm) reflective CsI,$^{12,14}$ NaI,$^{13}$ and CsBr (Ref. 21) photocathodes can be substantially augmented by their post-evaporation heating for several hours at 50–90 °C. In a previous work, it was observed$^6$ that such treatment has no impact on the UV photoabsorption length of CsI, NaI and CsBr deposited films. Therefore, the quantum efficiency enhancement could be the effect of bulk or surface alterations resulting in a change of either the electron transport or the electron emission properties. Thus, the annealing effect on the UV photoelectron escape length has been investigated here for CsI, NaI and CsBr photocathodes. For this purpose, the experimental procedure described above was repeated when, after each evaporation step, the film substrate was heated to

![FIG. 2. The measured UV-induced photoelectron escape length as a function of the photon wavelength for our CsI films, as evaporated (full symbols) and after 3 h annealing at 80 °C (empty symbols). The dashed line represents the simulated values.](image)

![FIG. 3. The measured UV-induced photoelectron escape length as a function of the photon wavelength for our evaporated KI films (full symbols). The dashed line represents the simulated values.](image)

![FIG. 4. The measured UV-induced photoelectron escape length as a function of the photon wavelength for our evaporated RbI films (full symbols). The dashed line represents the simulated values.](image)

![FIG. 5. The measured UV-induced photoelectron escape length as a function of the photon wavelength for our NaI films, as evaporated (full symbols) and after 3 h annealing at 80 °C (empty symbols). The dashed line represents the simulated values.](image)
where \( ~80 \, ^\circ \text{C} \) by a halogen lamp at its back side, for 3 h and under high vacuum. Then, the photocathode was cooled back to room temperature and the photocurrent was measured as a function of the wavelength.

As can be seen in Figs. 2 and 6, respectively, the escape length data of CsI and CsBr heated photocathodes are in general within the error domain of normal photocathode values. However, as shown in Fig. 5, the annealing of NaI has resulted in a slight increase in the escape length, relative to nonheated films.

III. THEORY

A. Photoemission model

The details of our model of UV photoemission from alkali halides were exposed in our previous work,\(^5\) its general features will be described briefly. The model simulates the photoemission process as a sequence of steps: the UV photon absorption within the alkali halide, the transport of the re-emitted electron, and to energy gained by it through phonon absorption \((-\)\). \(e\) and \(m^*\) are the charge and the effective mass of the electron, \(h\omega_{opt}\) and \(E\) are, respectively, the energies of the optical phonon and of the incident electron. \(e\) and \(\varepsilon_{\infty}\) are the static and the optical dielectric constants and \(n(q_{opt})\) is the phonon occupation number. \(W_1^\pm\) and \(W_2^\pm\) are determined from energy and momentum conservation laws and are given in Ref. 23. For the acoustic phonon–electron interaction, Ashley et al.\(^{25}\) utilized Sparks et al.’s treatment\(^{25}\) and the inverse mean free path is

\[
A = \left( 1 - \frac{1}{2} \frac{\hbar \omega_{opt} / E}{(1 + \hbar \omega_{opt} / E)^{1/2}} \right) \ln \left( \frac{W_2^+ / W_1^+}{\hbar \omega_{opt} / E} \right) \tag{2}
\]

and where the subscripts refer to energy lost by the incident electron to the crystal by phonon emission \((+)\) and to energy gained by it through phonon absorption \((-)\). \(e\) and \(m^*\) are the charge and the effective mass of the electron, \(h\omega_{opt}\) and \(E\) are, respectively, the energies of the optical phonon and of the incident electron. \(e\) and \(\varepsilon_{\infty}\) are the static and the optical dielectric constants and \(n(q_{opt})\) is the phonon occupation number. \(W_1^\pm\) and \(W_2^\pm\) are determined from energy and momentum conservation laws and are given in Ref. 23. For the acoustic phonon–electron interaction, Ashley et al.\(^{25}\) utilized Sparks et al.’s treatment\(^{25}\) and the inverse mean free path is

\[
\left( \frac{1}{\lambda_{opt}} \right) = \frac{3S^2}{4\pi M_e N_c h v^*} \int_0^\infty dq \left\{ \begin{array}{l}
\frac{q^3}{\omega(q)} f(q) \\
\left( n(q) + \frac{1}{2} \right)^2 \left( 1 - \frac{q^2}{q_{max}^2} \right) \end{array} \right\} \tag{3}
\]

where \(M_p\) and \(N_c\) are, respectively, the primitive cell mass and density in the crystal. \((\hat{k},\hat{k}^*)^\pm, q_{max}\) and \(\omega(q)\) are given in Refs. 23 and 5. \(S\) is the interaction Hamiltonian matrix element and \(f(q)\) is the mass correction function.\(^{23}\) As in Ref. 5, the value of \(S\) is estimated using the scaling method of Sparks et al.\(^{23}\)

The velocity of sound, \(C_v\), appearing in the expressions of \((\hat{k},\hat{k}^*)^\pm, q_{max}\) and \(\omega(q)\), and the effective mass, \(m^*\), have been reconsidered. In our previous work,\(^5\) \(C_v\) and \(m^*\) were, respectively, taken as the sound velocity in the corresponding alkali metal and as the free-electron mass, \(m_0\). Here, the value of \(C_v\) in the various alkali halides was evaluated by means of the elastic theory\(^{26}\) and using the experimental elastic constant data of Bolef and Menes for single crystal alkali halides.\(^{27}\) The calculated \(C_v\) values were found to be consistent, within a few %, with Dash’s approximation for the sound velocity in solid films.\(^{28}\) The effective mass was determined following Fröhlich’s theory.\(^{29}\) For all the materials, \(h\omega_{opt}\), \(\varepsilon_{\infty}\) and \(e\) were taken from Ref. 30, except for NaI.\(^{31}\) The acoustic phonon values were obtained, for representative incident electron energies, by averaging the phonon energy over its momentum. The main parameter values used in this work are summarized in Table I.

TABLE I. Parameter values used in the theoretical model.

<table>
<thead>
<tr>
<th>Material</th>
<th>(\varepsilon_{\infty})</th>
<th>(e)</th>
<th>(C_v) (m/s)</th>
<th>(S) (eV)</th>
<th>(h\omega_{opt}) (eV)</th>
<th>(m^*/m_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI</td>
<td>3</td>
<td>5.65</td>
<td>1474</td>
<td>0.53</td>
<td>0.011</td>
<td>1.9</td>
</tr>
<tr>
<td>KI</td>
<td>2.7</td>
<td>5.1</td>
<td>1621</td>
<td>0.60</td>
<td>0.017</td>
<td>1.8</td>
</tr>
<tr>
<td>RbI</td>
<td>2.6</td>
<td>5.5</td>
<td>1415</td>
<td>0.46</td>
<td>0.013</td>
<td>2.1</td>
</tr>
<tr>
<td>NaI</td>
<td>2.9</td>
<td>7.3</td>
<td>1788</td>
<td>0.78</td>
<td>0.023</td>
<td>1.8</td>
</tr>
<tr>
<td>CsBr</td>
<td>2.8</td>
<td>6.5</td>
<td>1644</td>
<td>0.52</td>
<td>0.014</td>
<td>2.1</td>
</tr>
</tbody>
</table>

B. Electron escape length calculations

UV photoemission quantum efficiency calculations, based on the model, were performed by means of a Monte Carlo simulation code. First, the absorption depth of the in-
cident electron is selected according to our experimental mean absorption lengths for the considered materials. The trajectory of the released electron is followed step by step, where the interaction process is, at every step, chosen randomly according to the relative inverse mean free paths of the various electron–phonon interactions. After the incident electron undergoes an optical phonon–electron interaction, its scattering angle is selected according to the optical angular distribution [Eq. (7) in Ref. 5]. In the case of acoustic scattering, the angular distribution was not taken to be isotropic, as in Ref. 5, but was calculated (for every alkali halide considered) similarly to Ref. 32, and was found to widely favor large angular deflections (in general in the ~80–160° range). Since the distribution was quite flat, it was approximated by a uniform angular function over the mentioned range. The electron trajectory is examined until its energy becomes lower than the electron affinity of the material or until it reaches one of the alkali halide surfaces.

The energy gap, $E_g$, and the electron affinity, $\phi$, are important for the photoemission model parameters, which influence, respectively, the initial energy and the electron emission capability. Their values, as utilized in this work, are summarized in Table II. The energy gap values used in these calculations were taken from Ref. 33 for CsI (also consistent with Refs. 34 and 35), KI, RbI, and CsBr. The affinity values were provided by Ref. 36 for CsI (also Ref. 37), KI and RbI. In the case of CsBr, $\phi$ was determined from the difference between the photoemission threshold energy $E_{\text{g}}$ and the energy gap $E_g$ and $\phi$ values of NaI were extracted from Ref. 39.

For every alkali halide considered, the quantum efficiency value was calculated for various film thicknesses, as a function of the incident photon wavelength, up to the photoemission threshold vicinity. The thicknesses considered were taken from 50 nm and up to 75 nm, with steps of 5 nm, in order to keep as close as possible to the experimental procedure. The evaluated efficiencies were corrected for the minor variations of a few tens of %, the electron escape length being almost not altered by it, the typical uncertainty due to the choice of $E_g$ and $\phi$ being of the order of 4%. Therefore, these parameters appear to be critical for absolute photoemission efficiency estimations but seem to have no real impact on the electron transport evaluation. The number of simulated events was chosen between $2 \times 10^4$ and $2 \times 10^5$, depending on the order of the quantum efficiency magnitude. This number provided a typical statistical uncertainty of about 3% for the efficiency calculation, the resulting escape length uncertainty being less than 5%.

Figures 2–6 present the simulated escape lengths as a function of photon wavelength together with the experimental data, for CsI, KI, RbI, NaI and CsBr. As can be seen in Figs. 3 and 5, the agreement between the experimental attenuation length data and the simulated values is remarkable in the case of KI and NaI. For CsI and CsBr photocathodes, the measured data and the calculated values are fairly compatible; for photon wavelengths up to 186 and 160 nm, respectively, the deviation is, in general, less than 20%. However, simulated escape lengths of RbI are systematically underestimated by an order of 30%, relative to the experimental data.

One should mention that our calculations consider perfectly monochromatic UV light and thus do not account for the actual 4 nm UV source bandwidth. The electron escape length, in CsI, was calculated for a few representative photon wavelengths, where the monochromator resolution was taken into account. The obtained escape length deviation from the monochromatic estimate does not exceed 4%. In the case of the other alkali halides considered, the attenuation length dependence on wavelength is flatter and the bandwidth effect is expected to be even less significant. The comparison between measured and theoretically predicted attenuation lengths will be discussed in detail in Sec. IV.

### IV. DISCUSSION

From the calculations presented above, it appears that there is in general a fair agreement between experimental and calculated electron escape lengths. This is true despite the fact that the evaporated photocathodes are polycrystalline films and not perfect single crystals, as assumed in the theoretical model. This can easily be explained by the fact that in the electron energy range considered, the de Broglie electron wavelength, $\lambda_{\text{DB}}$, is on the order of magnitude of nm and is thus much smaller than the typical size of an evaporated crystal grain, i.e., around 200 nm. Therefore, the single crystal approach for the electron transport mean free path evaluation constitutes a justified approximation for modeling the photoelectron transport in alkali halide evaporated films.

Lacer and Garwin’s method, used for calculating the inverse mean free path of the optical phonon–electron scattering [Eq. (1)], is based on the macroscopic polarization field theory of Fröhlich. This approach thus assumes that the lattice can be treated as a continuum and is valid only if the interaction mean free path is comparatively large to the lattice constant. Moreover, Fröhlich’s model utilizes the time-dependent perturbation theory. It thus requires that the eigenstate of the unperturbed electron should be stable enough in the de Broglie wavelength scale before...
scattering,\textsuperscript{40} i.e., the interaction mean free path has to be on the order or larger than $\lambda_{DB}$. For the alkali halides investigated in this work, the lattice constant values vary between 0.44 nm (CsBr) and 0.73 nm (RbI)\textsuperscript{41} and $\lambda_{DB}$ is, as mentioned above, about 1 nm. Therefore, these requirements are not fulfilled in the materials considered for electron energies on the order of a few tenths of eV and the theory is thus not applicable around the alkali halide photoemission wavelength threshold, where the released electron energy is low. This issue was first emphasized by Llacer and Garwin.\textsuperscript{24}

As observed above, it is not clear whether the post-evaporation thermal treatment of thin CsI, CsBr and NaI photocathodes has an impact on the measured electron escape length. In the case of CsI and CsBr, no influence was remarked. For NaI, the heating was followed by a small increase in the escape length. No annealing effect on the measured photoabsorption length in the materials mentioned was observed.\textsuperscript{6} Therefore, bulk modifications could be eliminated as a possible cause for temperature-enhanced quantum efficiency previously observed in 500 nm thick films,\textsuperscript{13} although the films investigated here and in Ref. 6 are an order of magnitude thinner and thus could exhibit a different crystalline structure. An effect that could speak for surface modifications of the annealed films is the observed increase in the photocurrent, particularly in CsBr (a few tens of %) and in NaI (factor of 10). The annealing could have resulted in lowering the electron affinity. This hypothesis, already proposed by Buzulutskov et al.,\textsuperscript{13} is also supported by the fact that the affinity of NaI (1.5 eV) is considerably larger than that of CsI (0.1 eV) and CsBr (0.4 eV) and thus is more susceptible to being lowered by the heating. Another or additional effect could have happened in NaI, which is known to be a very hygroscopic material. The heating could induce a removal of residual water molecules from the surface and thus improve the electron emission.

V. CONCLUSIONS

The electron escape length in CsI, KI, RbI, NaI and CsBr has been derived as a function of the incident UV photon wavelength, by measuring in transmission mode the photocurrent dependence on the alkali halide film thickness. The electron escape length data are in the 10–40 nm range. Our UV photoemission model was used for calculating theoretical escape length values in the materials mentioned. In general, there is a fair compatibility between experimental and predicted values. Therefore, electron interactions with both optical and acoustic phonons, as assumed in the model, appear to describe in a realistic way the physics of the electron transport in alkali halide photocathodes. The experimental electron escape lengths have also been found to be consistent with that evaluated from x-ray photoemission yield data.

The influence of a post-evaporation thermal treatment was investigated and it does not appear to be significant in CsI, CsBr and NaI evaporated films. Surface modifications resulting in a decrease of the electron affinity, rather than bulk structure changes, seem therefore to be a likely reason for the considerable quantum efficiency enhancement observed in the past in annealed thick alkali halide reflective photocathodes. The influence of heating on the alkali halide electron affinity can be investigated by comparing experimental quantum efficiency data for nonheated and heated photocathodes to theoretically predicted values.

Since our theoretical approach for estimating the low energy electron transport in alkali halides appeared to be successful, it will be shortly utilized for calculating characteristics of UV photoemission from alkali halide films and also for trying to understand the UV photoemission enhancement caused by an external electric field in CsI reflective photocathodes.\textsuperscript{43} In addition, the model presented in this work will be used in the frame of a theoretical approach for estimating the features of the secondary electron emission induced from alkali halides by x rays or energetic electrons.

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\textsuperscript{2}A. Breskin, A. Buzulutskov, R. Chechik, M. Prager, and E. Shefer, Appl. Phys. Lett. 69, 1008 (1996).
\textsuperscript{5}A. Akkerman, T. Boubloul, A. Breskin, R. Chechik, and A. Gibrekhterman, J. Appl. Phys. 76, 4656 (1994).
\textsuperscript{17}C. Lu (private communication).
21 E. Shefer, A. Breskin, R. Chechik and N. Avraham (unpublished).