



HAL
open science

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at very low energies

Janina Löffler, Mohamed Belhaj, Nenad Bundaleski, Juan J Diaz Leon,
Jonathan Thomet, Samira Frey, Christophe Ballif, Nicolas Wyrsh

► **To cite this version:**

Janina Löffler, Mohamed Belhaj, Nenad Bundaleski, Juan J Diaz Leon, Jonathan Thomet, et al..
A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at very low energies. *Journal of
Physics D: Applied Physics*, 2023, 56 (6), pp.063506. 10.1088/1361-6463/acaf37 . hal-04061323

HAL Id: hal-04061323

<https://hal.science/hal-04061323v1>

Submitted on 6 Apr 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

ACCEPTED MANUSCRIPT

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies

To cite this article before publication: Janina Löffler *et al* 2022 *J. Phys. D: Appl. Phys.* in press <https://doi.org/10.1088/1361-6463/acaf37>

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is © 2022 IOP Publishing Ltd.

During the embargo period (the 12 month period from the publication of the Version of Record of this article), the Accepted Manuscript is fully protected by copyright and cannot be reused or reposted elsewhere.

As the Version of Record of this article is going to be / has been published on a subscription basis, this Accepted Manuscript is available for reuse under a CC BY-NC-ND 3.0 licence after the 12 month embargo period.

After the embargo period, everyone is permitted to use copy and redistribute this article for non-commercial purposes only, provided that they adhere to all the terms of the licence <https://creativecommons.org/licenses/by-nc-nd/3.0>

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions will likely be required. All third party content is fully copyright protected, unless specifically stated otherwise in the figure caption in the Version of Record.

View the [article online](#) for updates and enhancements.

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies

Janina Löffler^{1,2}, Mohamed Belhaj³, Nenad Bundaleski⁴, Juan J. Diaz Leon⁵, Jonathan Thomet¹, Samira Frey¹, Christophe Ballif^{1,5}, Nicolas Wyrsh¹

¹Photovoltaics and Thin-Film Electronics Laboratory, Institute of Electrical and Microengineering (IEM), Ecole Polytechnique Fédérale de Lausanne (EPFL), Neuchâtel, Switzerland, ²HES-SO Valais-Wallis, HES-SO University of Applied Sciences and Arts Western Switzerland, ³ONERA-DPHY, 2 avenue E. Belin, 31055 Toulouse, France, ⁴CEFITEC, Departamento de Física, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Quinta da Torre, 2829e516 Caparica, Portugal, ⁵CSEM Sustainable Energy Center, Jaquet-Droz 1, 2002 Neuchâtel, Switzerland

E-mail: janina.loffler@hevs.ch

November 2022

Abstract. Recently developed microchannel plates based on amorphous silicon offer potential advantages with respect to glass based ones. In this context, secondary electron emission at very low energies below 100 eV has been studied for relevant materials for these novel devices. The aim of this work was to quantify the low energy electron emission - secondary emission and elastic scattering - from amorphous silicon and alumina and the dependence of the emission energy distribution on the primary electron energy, which was previously unknown. Secondary emission and energy distribution were both modelled and measured using equipment particularly designed for this energy range. The effects of roughness, angle of incidence and surface composition were analysed. We show crossover energies as well as the angular dependence of electron emission from amorphous silicon and alumina, with a maximum experimental emission yield value of 2 and 2.8, respectively, at an incident angle of 75°. A parameterization for the energy dependence of the emission energy spectrum at low energies was derived. This extensive analysis is fundamental for a comprehensive understanding of the performance of amorphous silicon-based microchannel plate detectors. It provides a complete model for secondary electron emission for a detailed description of the detector operation. The present results thus set the basis for a simulation framework, which is an essential element to increase the performance of these detectors and enable further developments.

Keywords: secondary electron emission, electron emission energy, a-Si:H, Al₂O₃, high secondary electron emissive layers, microchannel

Submitted to: *J. Phys. D: Appl. Phys.*

4
5 **1. Introduction**

6
7 Secondary electron emission (SEE) is a fundamental physical phenomenon behind the
8 working principle of electron multipliers. The latter represent a wide class of devices
9 that provide sensing of low intensity radiation, down to the detection of single particles.
10 An energetic electron impinging a dynode of a discrete electron multiplier produces
11 several secondary electrons, which are then accelerated towards the next dynode. In
12 the following collisions the electrons are further multiplied, resulting in an electron
13 avalanche, eventually providing a current pulse per each particle impinging the detector.

14
15 We see from the previous example that the total electron yield (TEY), defined as
16 the average number of electrons emitted per incident primary electron, is of extreme
17 importance in electron multipliers. More precisely, dependence of the TEY on primary
18 electron energy plays an essential role in their design and operation. The second
19 important feature of SEE, from the perspective of electron multipliers, is the energy
20 distribution of emitted electrons, since the initial electron energy determines both the
21 electron trajectory and its impinging energy onto the next dynode.

22
23 Glass based microchannel plates (MCPs) are electron multipliers with high spatial
24 resolution of the order of tens to hundreds of μm that were developed in the 1970s
25 (Ladislas Wiza (1979)). However, both the collection efficiency, i.e. the probability that
26 a particle will enter a channel, and temporal resolution of MCPs are limited as channel
27 geometries and the vertical conductivity are largely fixed. State-of-the-art clean room
28 processes have recently enabled fabrication of a novel electron multiplier with high
29 resolution based on hydrogenated amorphous silicon (a-Si:H) (Franco et al. (2014))
30 with the potential to overcome the inherent limitations of MCPs. Amorphous silicon
31 based microchannel plates (AMCPs) can be integrated monolithically and the vertical
32 conductivity can be adjusted through doping. AMCP channel spacing and diameters
33 can be customized down to narrow diameters below $3\ \mu\text{m}$ (Löffler et al. (2018)). During
34 the fabrication of AMCPs, channels with walls having different surface morphologies can
35 be realized, which could additionally increase TEY. Another strategy in improving MCP
36 performances is to deposit high TEY materials on the inner walls using atomic layer
37 deposition (ALD), which is known to make conformal coatings even over nanostructured
38 surfaces (Elam et al. (2006)). Although layers with higher secondary electron emissivity
39 can be deposited by ALD, Al₂O₃ layers are particularly suitable for this purpose due to
40 the well-established and broadly available technology.

41
42 From the gain of AMCPs, the average number of collisions inside the channel has
43 been calculated by Löffler et al. (2018). With a number of collisions of at least 6
44 and a bias voltage of 500 V, secondary electrons that are emitted with few eV gain
45 an average of about 80 eV. An average energy of 40 eV has been found by Frey et al.
46 (2019) for electrons that exit the channels. Knowing that electron paths between two
47 collisions inside the channel become even shorter for high aspect ratio AMCPs with
48 smaller channel diameters, electrons inside those channels hardly gain kinetic energies
49 above 100 eV. Therefore, designing AMCPs with the most suitable architecture requires
50
51
52
53
54
55
56
57
58
59
60

detailed understanding of SEE from this particular material in the energy range which is rarely investigated, i.e. below 100 eV. Thus, the present analysis is key to understanding the full potential and the limits of AMCPs, and to be able to assess their performance as a function of device geometries and surface morphology of the channels.

Low energy electron-matter interaction is a subject of great uncertainty with measurements of the TEY at 0 eV being controversial, as discussed by Andronov et al. (2013). Most of the commonly used physical models are inadequate for electron energies below 50 eV (Kieft and Bosch (2008)), implying that TEY modelling is also unreliable. While more accurate theories for low energy electron scattering are still to be explored, we have to rely on TEY measurements in this energy range. The latter, being a challenge on their own, have been performed mainly for materials that are used in space technologies by Balcon et al. (2012) including for metals such as Cu by Schulte et al. (2020), Ag, Au and crystalline silicon (c-Si) by Pierron et al. (2017). Further experimental difficulties originate when performing such measurements on non-conductive surfaces prone to surface charging.

In this paper, we extended the low energy SEE studies to a-Si:H and ALD-deposited Al₂O₃. A setup presented by Belhaj et al. (2010), highly suitable for TEY measurements from non-conductive surfaces, was used to determine the previously unknown TEY of a-Si:H and Al₂O₃ surfaces for energies below 100 eV. In addition, the energy spectra of emitted electrons from the same surfaces for primary electron energies below 200 eV were measured using a setup particularly designed for such purposes by Villemant et al. (2017). The importance of this investigation is in the ability to follow the change of the overall spectra (e.g. the relative contribution of elastically backscattered electrons) with the primary electron energy. Furthermore, the study can be extended to other high TEY coatings, such as MgO and composite structures.

In parallel to the experimental investigations, we used Monte Carlo (MC) simulators and analytical models. Furthermore we developed an original approach to consider the influence of surface morphology on TEY and applied it to the materials of interest. This allowed us to evaluate their capabilities in describing SEE phenomena at low primary energies in the case of a-Si:H and Al₂O₃ and thus their utility potential for future AMCP simulators.

2. Materials and methods

2.1. Sample preparation

The thin films of a-Si:H and Al₂O₃ used in this study were deposited on HF cleaned polished c-Si wafer substrates by means of plasma enhanced chemical vapor deposition (PECVD) and ALD, respectively. Two different procedures were used for the deposition of a-Si:H, yielding distinct surface morphologies i.e. roughness. Some of the a-Si:H films were additionally coated by Al₂O₃.

The film thickness of both resistive materials studied here was kept as thin as

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 4

possible in order to minimize charging problems, yet thick enough to measure electron emission from the film itself. Since the minimal film thickness is given by the secondary electron escape depth of few nm (Fitting et al. (2001)), all a-Si:H layers in this study were aimed to be about 15-20 nm.

The PECVD setup and deposition recipe of a-Si:H were described in detail by Franco et al. (2014). Rough surfaces were produced using the aforementioned recipe applied for the deposition of AMCP layers. Briefly said, the former deposition recipe is optimized for low intrinsic stress for the deposition of thick layers, resulting in a corrugated surface, when deposited as a thin film of few nm. Additionally, a procedure optimized for surface flatness was used to deposit a second set of samples. By comparing the SEE properties of the two types of films, we were able to estimate the influence of surface morphology on the overall secondary electron emission behaviour.

Al₂O₃ was deposited in an Oxford FlexAl ALD setup using a mixture of Trimethylaluminum (Al₂(CH₃)₆) and water. The thickness of the deposited films was about 5 nm on both the corrugated a-Si:H surface and the substrate surface (used as the reference sample).

Thickness of thin films was measured with an ellipsometer and interpreted using the dispersion model developed by Cauchy (1830).

2.2. Surface characterization

The two main characteristics of surfaces, i.e. their topography and their chemical composition, govern the process of secondary electron emission. We analysed the topography using an atomic force microscope (AFM) Bruker VT-102-2. The data analysis was performed using Gwyddion v.2.58. Surface chemical composition analysis was performed by means of X-ray photoelectron spectroscopy (XPS). The XPS setup consists of a monochromatic X-ray gun with Al anode, providing a photon energy of 1486.7 eV, and a hemispherical electron energy spectrometer. The spectra were acquired in the fixed analyzer transmission mode with the pass energy of 200 eV. The line intensities were determined after removal of the background of Shirley type. The composition was determined using appropriate sensitivity factors, under the assumption of in-depth uniform samples. Hydrogen concentration was not measured. In general, it is about 5-20% in a-Si:H, with a hydrogen rich surface (Blayo and Drévillon (1992)). Hydrogen on the surface can be present as adsorbed H₂O and is usually removed by annealing in AMCPs, as described by Franco (2014).

2.3. SEE measurements

SEE measurements were performed on the ALCHIMIE and DESSE facilities located at Onera, both providing a base pressure of 10⁻¹⁰ mbar.

The TEY was measured at ALCHIMIE/DEESSE using a charge collection method with a pulsed electron beam, which has been proven to avoid charging effects and consequently enables an accurate measurement of the electron emission yield of insulators at low

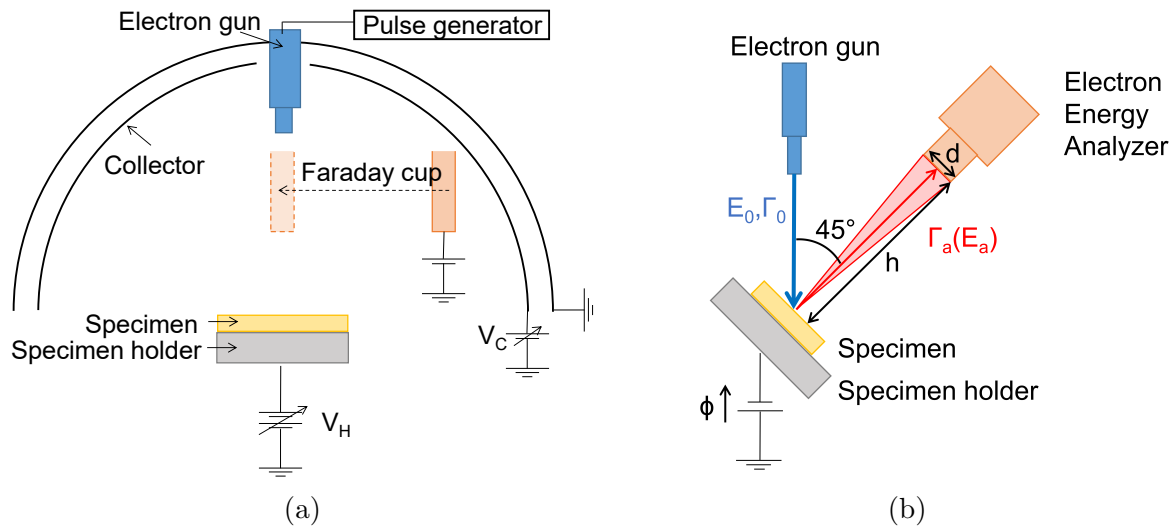


Figure 1: (a) Experimental setup for total electron emission yield measurements. The sample was tilted at various angles for an electron beam incidence from 0° up to 75° , relative to the surface normal. (b) Electron energy analyzer for characterization of the emission energy distribution. The sample was mounted at 45° with respect to the incident beam. This analyzer was calibrated for low energies by Villemant et al. (2017).

energies. The method and setup employed in this work were described in detail by Belhaj et al. (2010). The schematic of the setup is presented in figure 1a. The incident electron angle was varied from normal incidence (0°) up to 75° . The incident electron energies ranged from 10 to 1000 eV. The primary electron current was measured by a Faraday cup that was introduced between the electron gun and the sample holder. For each incident energy, 10 pulses of 6 ms and a current in the nA range were delivered. The TEY was calculated as the ratio between the sample charge and the incident charge.

The energy distribution of the emitted electrons was measured for electron irradiation with different incident energies using the hemispherical electron energy analyzer Omicron EA 125 of DEESSE, suitable for an energy range from few eV to 2 keV. The energy spectrometer was working in the fixed analyser transmission regime, with the electron pass energy of 200 eV. The schematic of the setup inside the vacuum chamber is shown in figure 1b. The samples were tilted by 45° with respect to the incident beam with monochromatic energy E_0 and the emission energy analyzer was facing the sample plane. The sample was kept at a bias of $\varphi = -11.5$ V. For an incident electron energy E_0 and flux Γ_0 , electrons with energies E_e in the range from 0 eV to E_0 were emitted from the sample.

The energy E_a recorded at the analyzer was

$$E_a = E_e - e\varphi + (\phi_{\text{sample}} - \phi_{\text{spectrometer}}) \quad (1)$$

with the elemental charge e and the respective work functions of the sample and the spectrometer, ϕ_{sample} and $\phi_{\text{spectrometer}}$. An extensive correction was elaborated for low energy emission spectra measurements by Villemant et al. (2017), as the electron energy

1
2
3 *A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies* 6

4 analyzer is typically calibrated for energies higher than 300 eV. Additionally, geometrical
5 constraints due to the limited field of view of the analyzer were taken into account.
6 In summary, the emission spectra were obtained from the recorded spectra $\Gamma_a(E_a)$ at
7 energies E_a with an energy step $\Delta E = 0.2$ eV as follows:
8
9

$$10 \quad N(E_e) = \frac{1}{\sum_{i=1}^M \left(\frac{\Gamma_a(E_i)}{H(E_i, \varphi)} \right)} \cdot \frac{\Gamma_a(E_a)}{H(E_e, \varphi) \Delta E}, \quad (2)$$

11 where $N(E_e)$ is the normalized emission probability at energy E_e . The transfer function
12 $H(E_e, \varphi) = H_T(E_e, \varphi) + H_a(E_a)$ is composed of:
13
14

$$15 \quad H_a(E_a) = \begin{cases} A \cdot \exp(\alpha \cdot E_a) & \text{for } 0 \leq E_a < 124 \text{ eV} \\ 1 & \text{for } E_a \geq 124 \text{ eV,} \end{cases} \quad (3)$$

16 with $A = 0.0192$ and $\alpha = 0.0319$ for the correction of the analyzer calibration and
17
18

$$19 \quad H_T(E_e, \varphi) = \begin{cases} 1 & \text{for } 0 \leq E_e \leq 3.25 \text{ eV} \\ \frac{\arctan\left(\frac{d}{2 \cdot h}\right)}{\arctan\left(\sqrt{\frac{E_e}{|\varphi|}}\right)} & \text{for } E_e > 3.25 \text{ eV,} \end{cases} \quad (4)$$

20 with $d = 0.03$ m and $h = 0.03$ m for the geometrical correction.
21
22
23

24 *2.4. SEE modelling*

25 We used existing MC tools, Nebula by van Kessel and Hagen (2020) and Casino by
26 Demers et al. (2011), to model SEE. Nebula was used with the modelling setup described
27 by Löffler et al. (2019). The number of primary electrons in all Nebula results shown
28 throughout this paper was 10^6 . The electron-material interaction simulator 3D Casino
29 ver. 3.3 has been used with the standard physical models implemented, using the
30 scattering cross section of the ELSEPA code by Salvat et al. (2005) and the energy loss
31 model by Joy and Luo Joy and Luo (1989). For each incident energy between 10 eV and
32 300 eV we simulated 3000 electrons for incident angles of 0° and 80° .
33
34

35 In addition, we used a novel simplified approach to model the energy dependence of
36 total electron yield TEY(E) from corrugated surfaces. The latter represents an extension
37 of the earlier work by Bundaleski et al. (2015), in which we predicted TEY(E) from a
38 smooth surface for an arbitrary incident angle from the experimentally measured TEY
39 at normal incidence. As an input to the model TEY(E) from the flat in depth uniform
40 sample measured at normal incidence is used. Then, an AFM image of the actual
41 emitting surface, representing the corrugation function $z(x,y)$, is used to calculate the
42 TEY(E) of that surface. The surface is considered as a mosaic of K flat areas, each
43 having an arbitrary inclination with respect to the surface normal of a perfectly smooth
44 sample. We used the AFM image to determine the local inclination at a point ' i ' of the
45 sample surface and the corresponding $\text{TEY}_i(E)$ according to the model by Bundaleski
46 et al. (2015). The trajectory of each of the N electrons leaving the surface was monitored.
47 These electrons were ejected from the point ' i ', with random outgoing angles following a
48
49
50
51
52
53
54
55
56
57
58
59
60

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 7

cosine distribution. If the number of electrons that managed to leave the surface without colliding with the surface protrusions is M_i , the TEY(E) of the corrugated surface is estimated as

$$\text{TEY}(\text{E}) = \sum_{i=1}^K \frac{M_i}{N} \cdot \text{TEY}_i(\text{E}). \quad (5)$$

The major drawback of this approach in modelling TEY from realistic surfaces is the assumption that the sample is indeed in-depth uniform. Besides, we neglect emission of the second generation of electrons, emitted due to impingement of the emitted electrons hitting the surface protrusions.

3. Results and discussion

3.1. Thin film characterization

We considered in this work four different samples, summarized in Table 1 together with their surface morphology parameters:

- Sample 1 is the corrugated a-Si:H layer (rough);
- Sample 2 is the smooth a-Si:H layer (flat);
- Sample 3 is the corrugated a-Si:H layer coated by Al₂O₃ (rough AlOx);
- Sample 4 is the smooth Al₂O₃ layer (flat AlOx).

Table 1: Thickness d and surface roughness S_a of all samples from Ellipsometry, including the surface roughness S_a of the underlying substrate or layer.

sample	top layer			substrate/lower layer	
	material	d [nm]	S_a [nm]	material	S_a nm
1 rough	PECVD a-Si:H	17	10	polished c-Si	< 1
2 flat	PECVD a-Si:H	12	< 2	polished c-Si	< 1
3 rough AlOx	ALD Al ₂ O ₃	5	10*	PECVD a-Si:H	10
4 flat AlOx	ALD Al ₂ O ₃	5	< 1*	polished c-Si	< 1

*Roughness given by the underlying substrate or layer

The typical surface topography of the samples fabricated with different roughness is shown in figure 2 and 3. Both figures show a $2 \times 2 \mu\text{m}^2$ AFM scan of a sample with $5 \times 5 \text{cm}^2$ overall surface area. AFM measurements were done with a Bruker AFM Dimension Edge with the AFM probe TESPA-V2, which has a nominal tip radius of 7 nm. The topography was measured in tapping mode and image analysis was done with Gwyddion (Nečas and Klapetek (2012)). All surface parameters were calculated according to ISO standards.

For the corrugated a-Si:H layer in figure 2, we measured an average roughness of $S_a = 1.8 \text{ nm}$, with a mesokurtic shaped surface with normal peaks and a kurtosis of $S_{ku} = 3.01$. The latter indicates height distribution close to a perfect Gaussian.

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 8

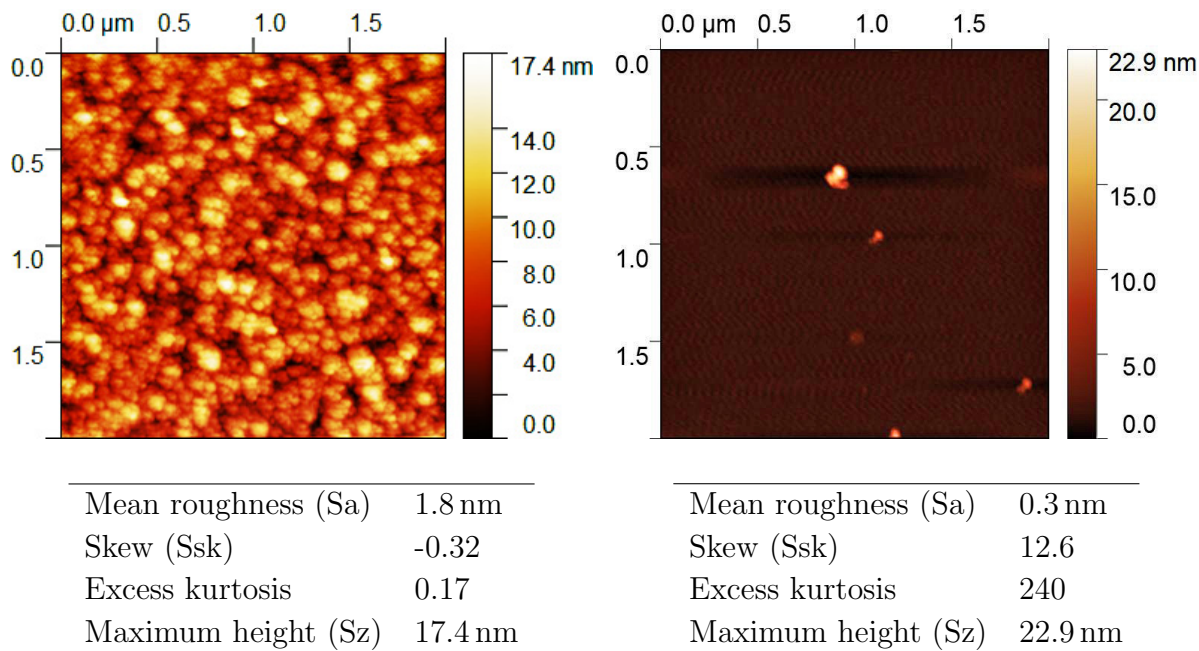


Figure 2: AFM scan of the rough a-Si:H sample and resulting surface parameters. Figure 3: AFM scan of the flat a-Si:H sample and resulting surface parameters.

For the smooth a-Si:H layer shown in figure 3, we measured an average roughness of $S_a = 0.3$ nm and a kurtosis of $S_{ku} = 239.88$. The high kurtosis value indicates rather steep and rare peaks.

Considering that ALD coatings are highly conformal, figure 2 and 3 illustrate the typical surface texture of the corrugated and smooth AlOx samples as well.

Since the surface composition controls the secondary emission, we used XPS to analyse the chemical composition of the samples as deposited. The samples were inevitably exposed to air to perform the post-fabrication analysis. Samples would need to be plasma cleaned inside the measurement setup in order to determine the secondary yield of the pure material a-Si:H. As AMCPs are not plasma cleaned before use, we measured the samples as deposited in order to determine a most comparable data set. An overview of their surface composition is given in Figure 4. Carbon is a standard surface contaminant present in all samples, typically in the form of adventitious carbon (saturated aliphatic hydrocarbons). We see that its relative amount is increased for both AlOx samples, being the result of the ALD coating process. Small quantities of fluorine in the same samples most probably have the same origin. No XPS analysis of the smooth sample was performed as it was expected to behave as the corrugated sample. Hydrogen content is not detected by XPS, both a-Si:H layers (corrugated and smooth) are typically composed of about 10% hydrogen.

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 9

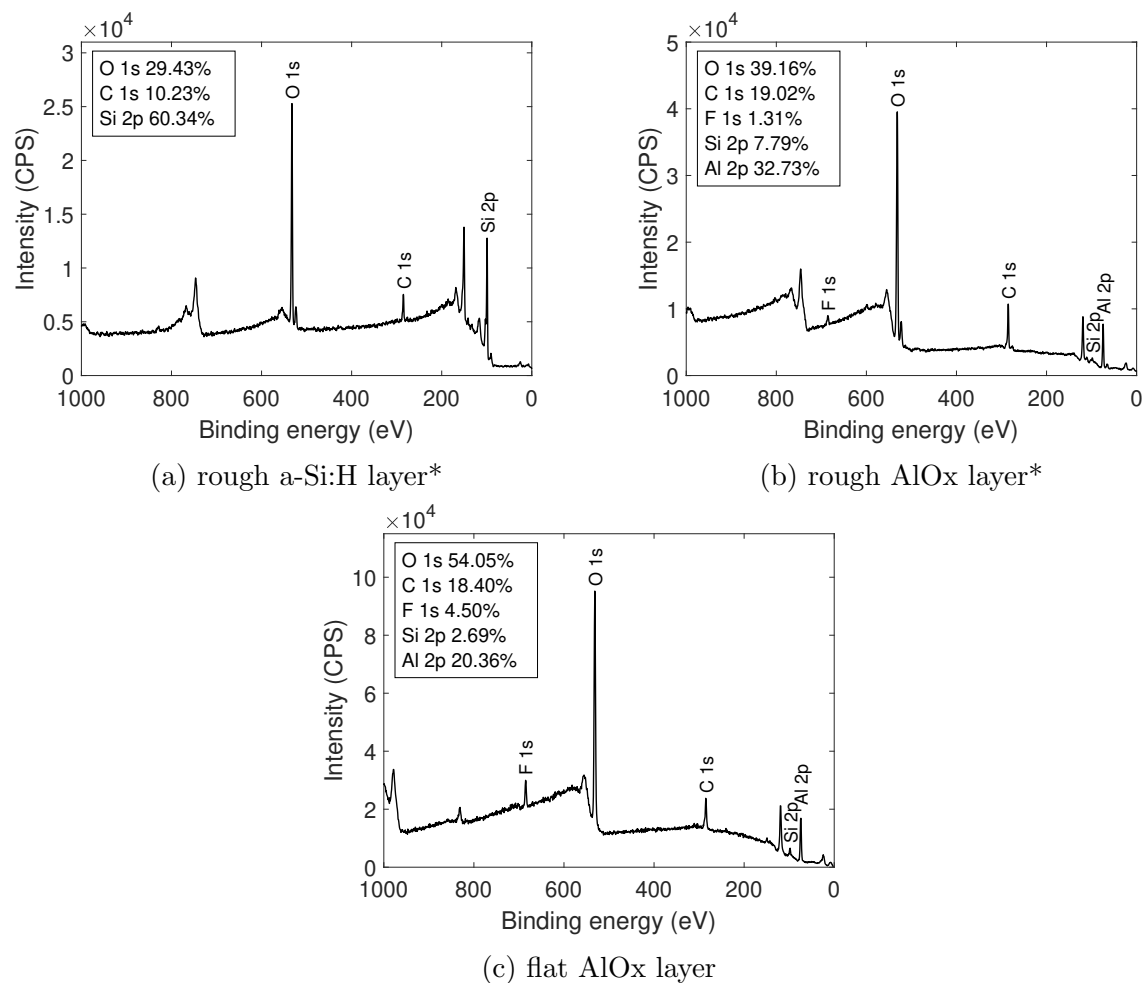


Figure 4: XPS spectra and resulting surface composition (atomic percent) of the corrugated a-Si:H layer and the corrugated and flat AlOx layer. *in situ XPS measurement

3.2. Emission yield

The TEY was measured for all samples at incident electron angles ranging from 0° (normal incidence) to 75° and for incident electron energies starting at 10 eV up to 1000 eV. Furthermore, the number of secondary electrons per incident electron, the secondary emission yield (SEY) was modeled for the AMCP surface.

3.2.1. Hydrogenated amorphous silicon The TEY of a-Si:H, measured for the corrugated and the smooth sample, is shown in figure 5. It was compared to experimental values of crystalline Si by Pierron et al. (2017); Bronshtein and Fraiman (1969) and from MC calculations by Pierron et al. (2017) and Kuhr and Fitting (1999). We also show the TEY of Si calculated with Nebula.

The measurements and simulations agree generally well for crystalline silicon, except for the low energy region where the more recent measurements by Pierron et al.

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 10

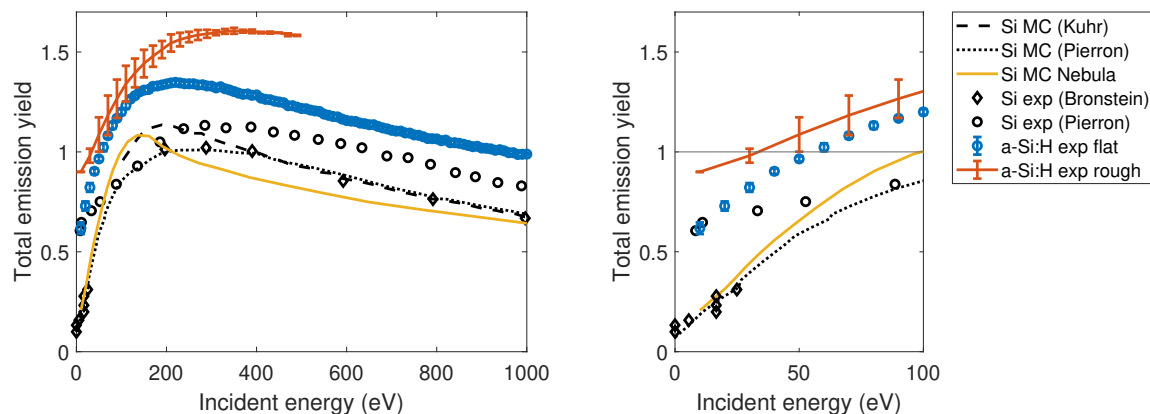


Figure 5: Total emission yield of a-Si:H measured for the smooth a-Si:H layer (flat) and the corrugated surface (rough) compared to literature values and simulations of crystalline Si.

(2017) show a higher yield than that predicted by the simulations. Of particular interest are the electron energies at which $TEY = 1$ (known as crossover energy), since the condition $TEY > 1$ is necessary to secure electron multiplication in MCPs. Compared to crystalline silicon, a-Si:H shows a higher emission yield and practically two times lower crossover energy of about 50 eV.

The incorporation of H into the atomic network of Si, yielding formation of a-Si:H, leads to H and OH termination. The overall effect is an increased electron emission yield of a-Si:H as compared to Si. This characteristic increase of the TEY due to H termination has also been observed for diamond by Shih et al. (1997). Indeed, electronic ab-initio calculations by Tao et al. (2015) have shown a decreased electron affinity of SiN through hydrogen termination, which effectively lowers the potential barrier for electron emission. The increase in emission yield observed here could thus be due to a lower potential barrier at the surface of a-Si:H. If this is not the case, the main reason for the increased TEY would be an increased energy gap, which forbids various energy loss processes and consequently extends the electron trajectories. The surface morphology of a-Si:H is also beneficial for secondary electron emission. With a maximum total emission yield over 1.6, the rough surface texture leads to a higher yield than the smooth surface. Additionally, we observe a further shift in the crossover energy of about 20 eV towards a lower energy for the corrugated a-Si:H sample compared to the smooth a-Si:H sample.

The TEY dependence on the incident angle is shown in figure 6. For higher incident angles we observe an increase towards higher yields. This is a well known phenomenon related with the deposition of the energy of primary electrons in a shallower region than at normal incidence. Therefore, the generated secondary electrons can be emitted with higher probability. This can be modeled for a number of pure conductive materials according to different approaches, such as the one presented by Bundaleski et al. (2015). It was demonstrated in the latter that the crossover energy shifts towards lower energies

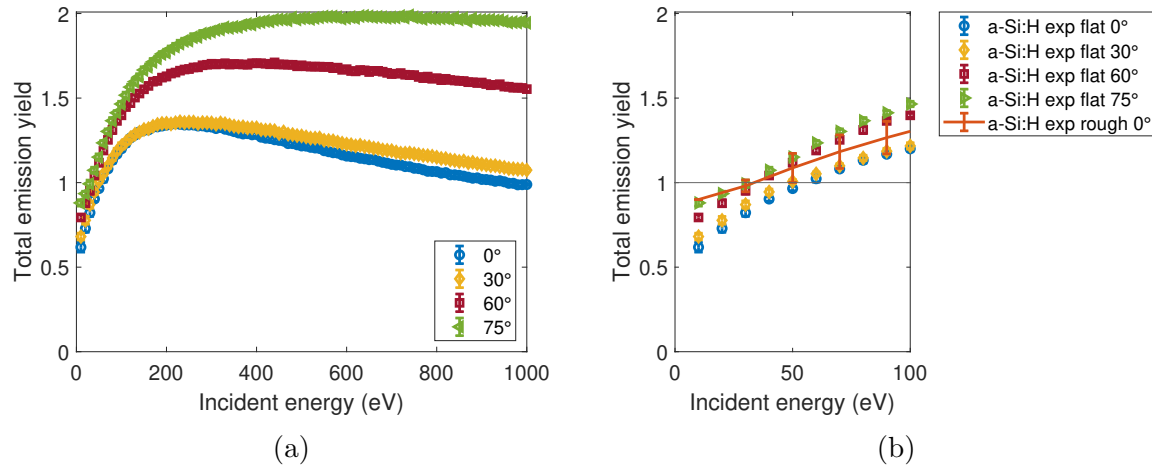


Figure 6: (a) Total emission yield of a smooth a-Si:H sample, measured at incident angles of 0°, 30°, 60° and 75°, starting at 10 eV. (b) A zoom shows the crossover energy of a-Si:H with different surface textures (corrugated and smooth samples) and angles.

with increasing incident angle. In figure 6, we compare the crossover energy of the smooth layer at 75° with the measurements and literature values already shown in figure 5. The crossover energy for the smooth layer at 75° is about 20 eV lower than that at normal incidence. A decreased crossover energy is observed for the corrugated surface even at normal incidence. Indeed, this is due to local surface inclinations of corrugated surfaces, which cause an oblique incidence of primary electrons. This frequently results in amplification of the secondary electron emission. Due to the increase in elastic scattering for even higher incident angles, Bundaleski et al. (2015) predict a maximum yield at about 70°. Therefore, the TEY should decrease with further increasing angle.

In AMCPs an average emission yield of about 1.6 at an average incident energy of about 70 eV has been inferred from gain measurements of AMCP devices by Franco et al. (2014). Given the rough surface texture inside AMCP channels, this assumption is in good agreement with the observed trends. Electrons are accelerated with grazing trajectories in AMCPs and local electric field gradients could be the reason for an even further increase of their electron emission yield.

3.2.2. Aluminum Oxide While the inherent TEY of a-Si:H layers can be enhanced by roughening its surface, highly emissive layers need to be used to further improve AMCP performances. Hence the use of materials that can be deposited via ALD, since it is the only method capable of uniformly coating the inside of a channel with high aspect ratio. We show the total emission yield of Al₂O₃ in figure 7, where the measurements and MC calculations are compared to literature values.

Calculated TEY include results of MC simulations by Ivanov et al. (2018) at the respective incident angles of 0° and 80°. van der Graaf et al. (2017) used a low energy MC extension of a GEANT4 code to obtain the curves presented here. Additionally to

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 12

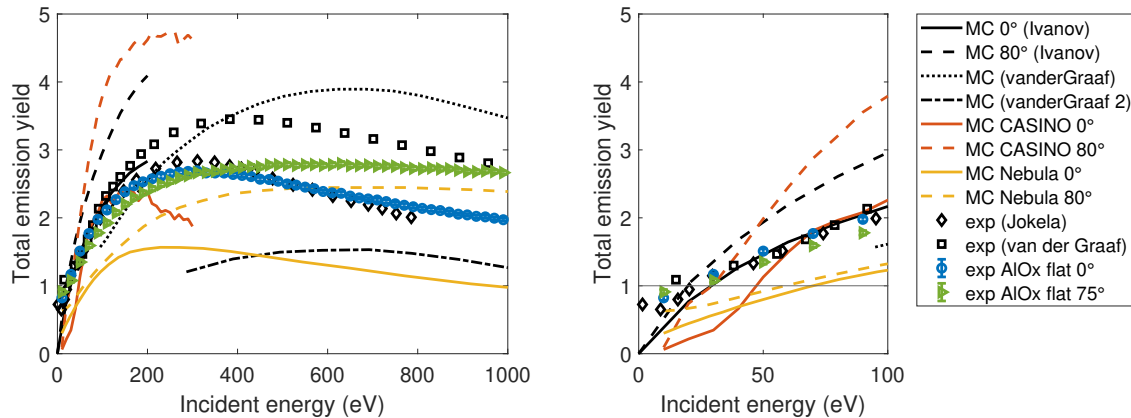


Figure 7: Al₂O₃ total emission yield measurements and simulations compared to experimental and calculated literature values.

results from Nebula, we show results from Casino. The total emission yield of Al₂O₃ has been measured experimentally by Jokela et al. (2012) for a 4 nm thick layer and by van der Graaf et al. (2017) for a 12.5 nm thick one. In figure 7, we show the experimental total emission yield of Al₂O₃ at 0° incidence and at 75° incidence.

It can be observed that the different assumptions in the theoretical models lead to a great variation of the resulting TEY. The experimental emission yield data on the other hand agree well, especially in the low energy range. A higher maximum yield of the experimental result by van der Graaf et al. (2017) could be due to the layer thickness. Thicker layers of Al₂O₃ are expected, theoretically, to exhibit a higher yield, when charging is avoided. As seen in the previous section, higher incident angles on flat layers also increase TEY. In reality the surface morphology, surface contamination and charging effects greatly affect experimental results. The TEY of the smooth of Al₂O₃ layer at 75° is below the expected increase with incident angle. This and the flattened shape of the curve indicate that this particular measurement was subject to charging.

The increase of the TEY on a corrugated a-Si:H layer by using a highly emissive Al₂O₃ coating is shown in figure 8. As the highly resistive a-Si:H layer leads to charging of the surface, the secondary yield of Al₂O₃ cannot be fully determined when deposited on this rough surface. However, despite this charging effect and a total layer thickness of about 22 nm, we observe a higher secondary electron yield with the additional Al₂O₃ coating compared to the yield of the 17 nm thick corrugated a-Si:H layer.

Typically, the ALD deposition temperature of Al₂O₃ is between 200°C and 300° (Guo et al. (2019)). We found that the deposition temperature has no significant effect on the TEY, as shown in figure 8. The smooth Al₂O₃ layer, prepared at 200°C and a similar layer deposited at 300°C with otherwise identical parameters exhibit almost identical TEY values.

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 13

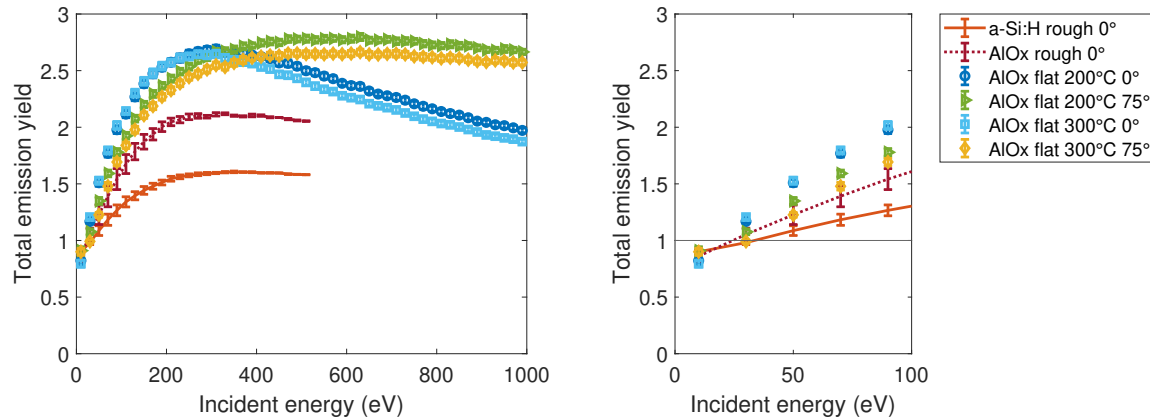


Figure 8: The total emission yield of Al₂O₃ (flat AlOx) fabricated at temperatures of 200°C and 300°C respectively, was measured at incident angles of 0° and 75°. The total emission yield of the corrugated a-Si:H layer is improved by an Al₂O₃ coating (rough AlOx), even though limited by charging when compared to the total emission yield of the smooth Al₂O₃ layer.

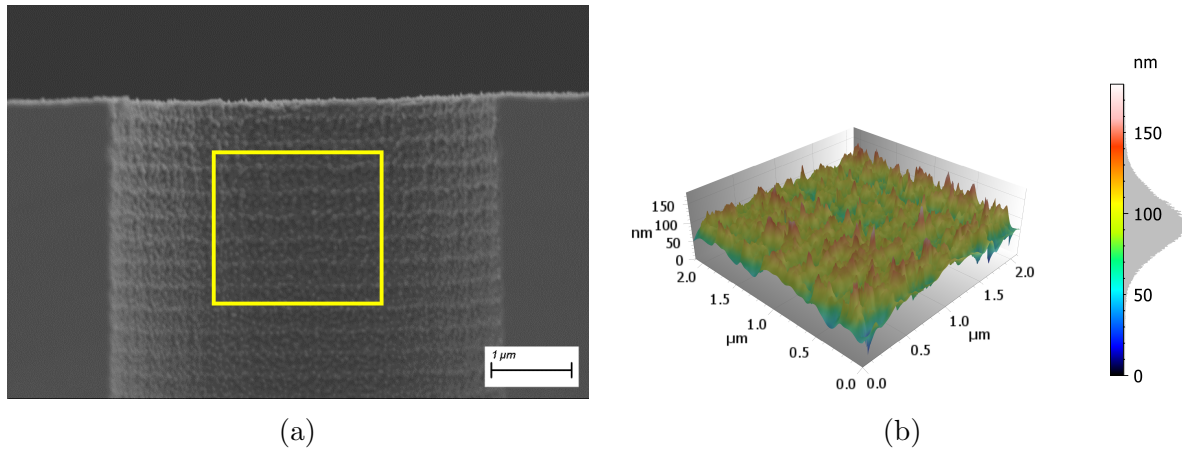


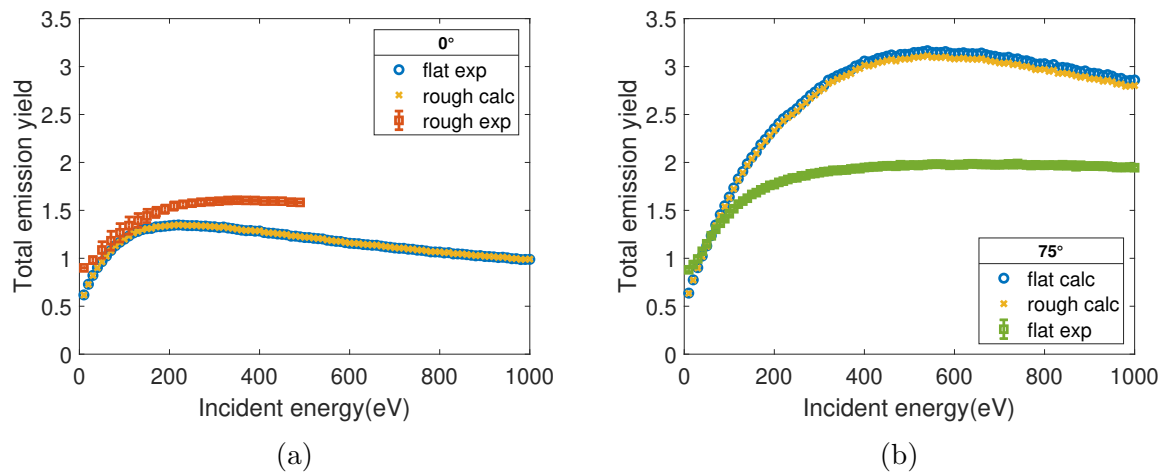
Figure 9: (a) SEM image showing the surface morphology inside an AMCP channel. (b) Height profile $z(x,y)$ and height distribution of the AMCP channel for the area marked in (a).

3.3. Total emission yield in AMCPs

How do the previous results allow one to deduce the TEY in AMCPs? As previously seen, the total emission yield largely depends on the surface morphology. Therefore, we considered the influence of the real surface structure in AMCP channels, shown in figure 9. In general, the surface inside the channel varies depending on the fabrication process and within one channel, along its depth. We also discuss the TEY for the limit of electrons with negligible energy approaching 0 eV.

1
2
3 *A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies* 14

4
5 *3.3.1. Modelling TEY of the AMCP channel surface* Using the measured TEY(E) of
6 smooth and corrugated a-Si:H layers shown in section 3.2.1, the expected emission yield
7 of a corrugated AMCP channel surface has been calculated based on the model described
8 in section 2.4. The aim of this calculation was to evaluate the possible effects of the
9 AMCP channel surface morphology on the TEY.
10
11
12



35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure 10: (a) TEY of the corrugated a-Si:H surface shown in figure 2 was calculated (rough calc) using TEY of the flat a-Si:H layer (flat exp) as a calibration and compared to the measurement (rough exp) at 0°. (b) TEY for the rough and the flat layer were calculated at 75° and compared to the experimental TEY of the flat layer.

As a first step, the expected emission yields of the smooth and corrugated a-Si:H layers were calculated from their surface scans. The smooth sample at 0° was taken from the experiment to calibrate the TEY(E) model. Hence, the calculated TEY at 0° (flat calc) corresponds to the measured TEY (flat), as shown in figure 10 a. The calculated TEY for the corrugated surface (rough calc) shows a similar yield. In figure 10 b, we show the calculated TEY at 75° for the smooth (flat calc) and corrugated surface (rough calc) and the experimental TEY for the smooth sample (flat). The difference in surface roughness does not lead to a significant difference in TEY according to the calculations. The experimental yield however is significantly different from the calculated ones. Since the experimental TEY cannot be explained by the surface roughness, other effects, like hydro-carbonation of the surface or, charging effects might have caused a lower experimental yield than expected for the corrugated surface as well.

The surface corrugation function $z(x,y)$ of the AMCP channel was reconstructed from an SEM image and is shown in figure 9. The expected TEY of this surface morphology was calculated (channel) and is shown in figure 11 alongside the calculated yield for the smooth surface (flat).

From the theoretical electron emission model, the surface morphology of the channel is expected to reduce the TEY, as electrons can be recaptured. In an operating AMCP on the other hand, the local electric field strength varies and could lead to re-emission

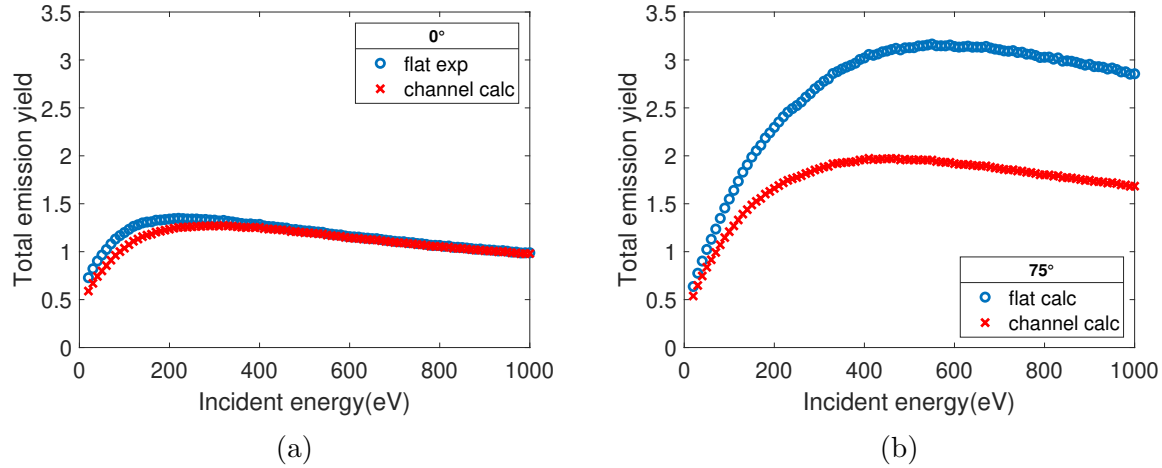


Figure 11: (a) TEY of the AMCP channel surface shown in figure 9 was calculated (channel calc) at 0° . The TEY of a perfectly smooth $a\text{-Si:H}$ layer (flat exp) at 0° served as a calibration. (b) The calculated TEY for the flat sample and for the channel surface are shown at 75° .

of electrons and a lowered crossover energy. This means that, in general, surface morphology alone cannot be used to calculate secondary yield in AMCP channels, and while TEY measurements of $a\text{-Si:H}$ layers can be used as a basis, the secondary yield of AMCPs must be deduced from AMCP gain measurements. Moreover, the maximum yield, and the yield curve at higher energies as just presented determine only a fraction of the electron dynamics, whereas the crossover energy plays a major role in determining the level of multiplication in the channel. The expected lowering of the crossover energy for corrugated surfaces could not be observed with the model.

3.3.2. Discussion - Total emission yield at low energies Overall, we found in the previous section that the total emission yield decreases below 1 only for energies below 40 eV. Notably, the measured TEY does not approach 0 when the incident energy approaches 0 eV. In fact, elastic scattering is the predominant process at low energies, as will be confirmed in the following section. However, the TEY for incident electrons with energies close to 0 eV might be prone to the following measurement artefacts. Electrons may not reach the surface and therefore not interact with the surface at all. Also, electrons may be absorbed. The nature of the interaction and the resulting TEY depend as well on the local work function, which is not uniform for the samples presented here. Furthermore, the electron beams used to measure TEY consist of electrons with an energy spread of about 0.8 eV. In theory, it can be assumed that $\text{TEY}(0\text{ eV})=1$ as discussed by Cazaux (2012), which has been shown experimentally for selected materials by Cimino et al. (2015). For AMCP modelling we assume hence a $\text{TEY}(0\text{ eV})=1$, where all electrons are backscattered, when absorption and other effects are neglected.

With the previous results, we provided an overview of the magnitude and slope of

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 16

the TEY at low energies as well as the crossover energies of a-Si:H and Al₂O₃ and their dependencies on surface corrugation and incoming angle. Due to the influence of the surface chemistry and texture on the emission yield, the AMCP channel surface cannot be fully represented as a thin film and thus cannot be fully characterized by electron emission measurements. However, the present study is a valuable starting point for the parametrization of emission yield curves in order to describe the multiplication process, in the low energy regime, in electron multipliers.

3.4. Emission energy

The goal of this analysis is to describe the operation of an AMCP channel, where we are studying an electron ‘cascade’: the energy of each emitted electron has a direct consequence on its incident energy and angle, which then affects the number of electrons emitted and trajectories in the forthcoming steps. As presented above, the number of emitted electrons depends on the incident electron energy. At a fixed electric potential and AMCP channel geometry, and assuming a cosine function for the emission angle of electrons, the incident energy and angle of an electron i.e. the TEY and therefore the number of electrons in the cascade solely depends on the electron emission energy.

The emission energy distribution $N(E_e)$ was measured for incident energies below 200 eV for the rough a-Si:H layer and the rough Al₂O₃ layer. The emission energy distribution was determined with the electron energy analyzer shown in figure 1b for the effective incident electron energies of 12.5 eV-192.5 eV for a-Si:H and 3.5 eV-194.5 eV for Al₂O₃, corrected according to the equation 2 and according to their work function taken from Cazaux (2010). The spectra are shown in figure 12.

Emitted electrons can be categorized according to the physical process they undergo when interacting with the surface: secondary electrons (SE), inelastically backscattered electrons (IBS) and elastically backscattered electrons (EBS). Because SE and IBS can not be separated at low energies and for the purpose of comparing the measurements with literature values, we artificially divide the spectrum into three parts, although this does not have a physical meaning. EBS are characterized by an emission energy close to the incident energy (+/- 2 eV). An emission energy both below 50 eV and 2 eV below the incident energy refers to a SE. The other electrons are considered as IBS. For primary electron energies below 50 eV we consider all electrons which are not EBS as secondary.

The TEY presented in section 3.2 is the sum of the secondary emission yield δ , the EBS yield η_e and IBS yield η_{ie} . Several empirical (Vaughan (1989)) and semi-empirical models (Bundaleski et al. (2015)) exist that describe δ . Therefore the resulting secondary yield curve can also be parameterized. The backscattering yield can also be described by existing models by Cazaux (2012); Cimino et al. (2004); Jablonski (2014). We used this categorization to obtain, with the help of the emission spectra measured at few energies shown above 12, probability functions for electron emission energies for all incident electron energies up to 500 eV. These functions could then be used for AMCP simulations.

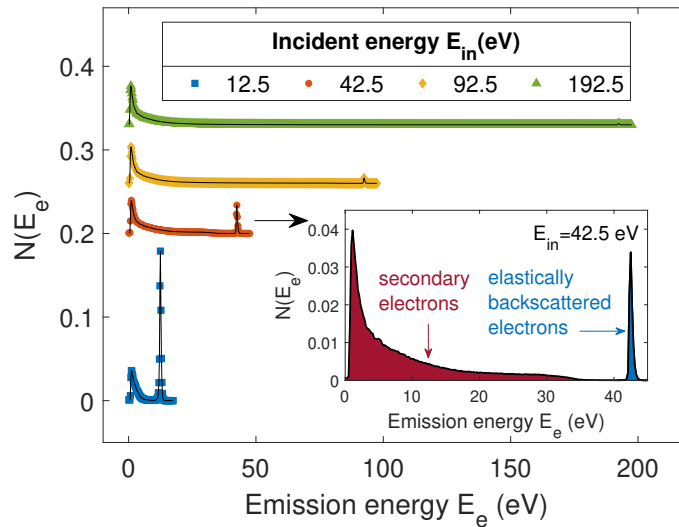
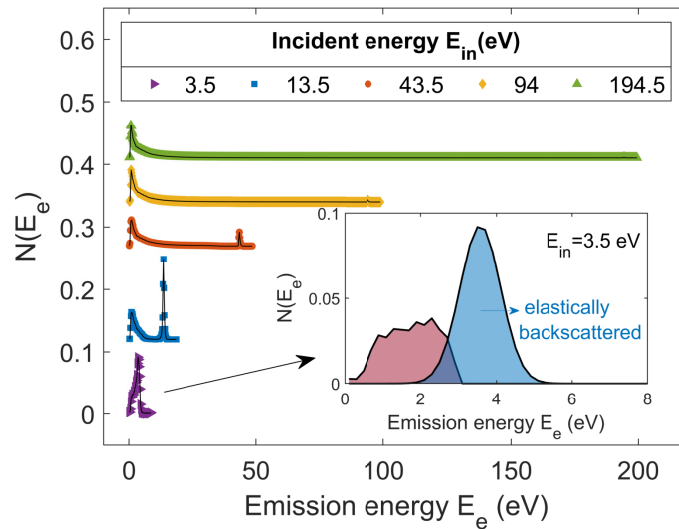
(a) *a*-Si:H(b) *Al*₂O₃

Figure 12: (a) Corrected *a*-Si:H emission spectra for incident energies of 12.5 eV, 42.5 eV, 92.5 eV and 192.5 eV. The inset shows the emission spectrum for 42.5 eV. We can identify the elastic peak at 42.5 eV, secondary electrons are all electron emitted with lower energies. (b) Corrected *Al*₂O₃ emission spectra for incident energies of 3.5 eV, 13.5 eV, 43.5 eV, 94 eV, 194.5 eV. The inset shows the emission spectrum for 3.5 eV, where the elastic peak overlaps with emission of electrons with less than the incident energy.

1
2
3 *A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies* 18

4
5 *3.4.1. Relative backscattering probability* At first, we used the energy spectra shown
6 above to deduce the relative backscattering probability P . P is a useful measure to
7 determine the relative proportion of high energy electrons versus low energy electrons
8 that are emitted upon an incident electron with a particular energy. P is particularly
9 useful in the event of elastic scattering, as all elastically backscattered electrons are
10 emitted with the same as the incoming energy and their total emission yield is 1.
11 The elastic and inelastic backscattering yields are related to P in the following way:
12 $\eta_{e/ie} = P_{EBS/IBS} \cdot TEY$. We calculated P_{EBS} as the integral of the elastic peak divided
13 by the integral of the whole emission function. Figure 12 a) shows an inlet for 42.5 eV,
14 where the area of the elastic peak is colored in blue, whereas the area of the secondary
15 electron distribution function is colored in red. Similarly, P_{IBS} is calculated from the
16 integral of the remaining energies between 50 eV and the elastic peak.
17
18
19
20

21 As shown in the spectra in figure 12, we measured $P_{EBS/IBS}$ in four points for a-
22 Si:H and in five points for Al₂O₃. In order to determine the backscattering probabilities
23 for every possible incident energy in AMCPs, the experimental data points were fitted
24 with an exponential decay function for the elastic contribution P_{EBS} and with a linear
25 function for the inelastic contribution P_{IBS} . The probability of elastic backscattering
26 at 0 eV was set to 1 $P_{EBS}(0) = 1$ as in Cazaux (2012). The functions $P_{EBS/IBS}$ were
27 arbitrary ones chosen to describe the experimental behavior:
28
29
30

$$31 \quad P_{EBS}(E_{in}) = (1 - a) \exp(-b \cdot E_{in}) + a \text{ for } E_{in} < 50 \text{ eV} \quad (6)$$

$$32 \quad P_{EBS+IBS}(E_{in}) = P_{EBS}(E_{in}) + c \cdot E_{in} + d \text{ for } E_{in} \geq 50 \text{ eV}. \quad (7)$$

33
34
35 The fit values are given in table 2.

36
37 Table 2: Fit values for the backscattering probability according to equations 6 and 7.

	a	b	c	d
a-Si:H	0.01	0.05	$4 \cdot 10^{-5}$	0.05
Al ₂ O ₃	0.005	0.06	$2 \cdot 10^{-5}$	0.03

38
39
40
41
42
43
44
45 We compared the incident electron energy dependence of the backscattering
46 probability measured here for a-Si:H with existing literature values of Si, and with the
47 results of MC calculations using Nebula and CASINO in figure 13. A similar comparison
48 is shown for Al₂O₃ in figure 14. An additional dependence of the backscattering
49 probability on the incident angle can be observed for both materials, which was not
50 taken into account in the parametrization. For both materials, variations in the relative
51 backscattering are important in the low energy range below 50 eV. Consequently, the
52 parametrization presented in this section can be used to separate the total emission yield
53 into its respective contributions and calculate electron emission energies in AMCPs.
54
55
56
57

58 *3.4.2. Secondary emission energy distribution* As secondary electrons drive AMCP
59 performance, quantifying their emission energies is crucial for an understanding of the
60

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 19

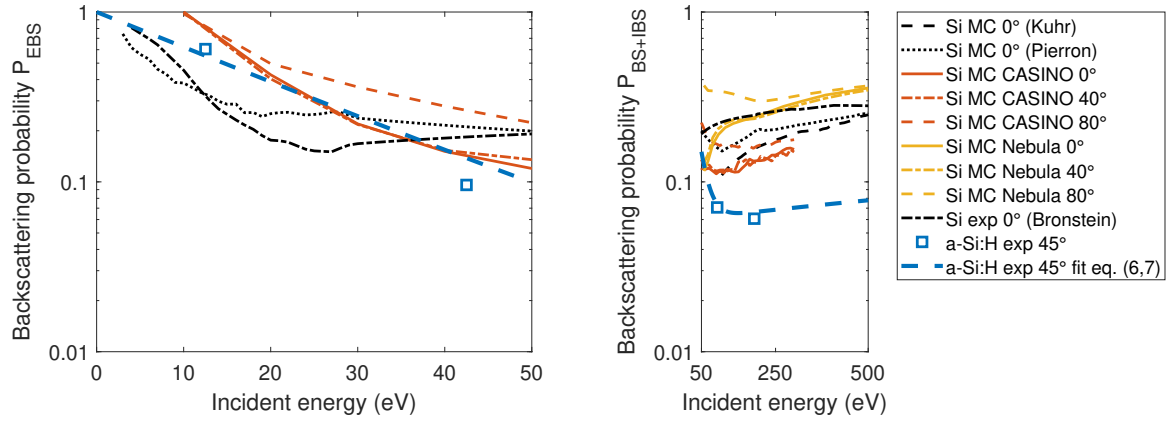


Figure 13: Experimental a-Si:H backscattering probability at 45°, measured at four points (see figure 12) and fitted with equations 6 and 7, compared to MC simulations, simulated and experimental literature values.

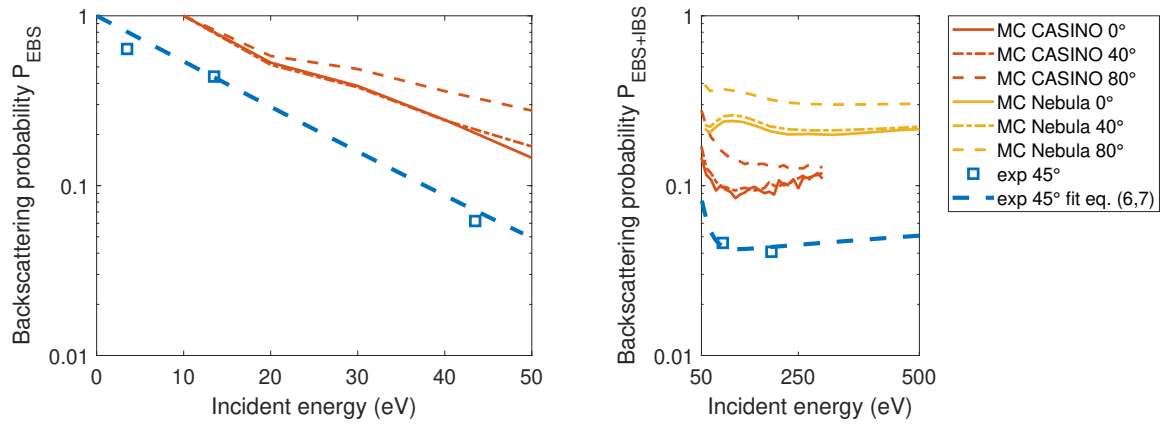


Figure 14: Experimental backscattering probability of Al₂O₃ measured at five points (see figure 12) and fitted with equations 6 and 7, compared to the simulation results and values found in the literature.

avalanche process in an AMCP channel. In this section, we compare the low energy part of the a-Si:H emission energy spectrum to theoretical and experimentally measured secondary electron energy E_s distributions $\partial\delta/\partial E_s(E_{in})$ of a-Si:H and c-Si in figure 15. While secondary electrons are commonly defined to have an energy cutoff at 50 eV, most of the secondary electrons are emitted with energies below 10 eV.

The analytical functions include a physics based model by Henke et al. (1979) with

$$d\delta/dE_s(E_s, \chi, E_g) = C \cdot \frac{E_s}{(E_s + \chi - E_g)^2 \cdot (E_s + \chi)^{5/2}} \quad (8a)$$

for semiconductors and

$$d\delta/dE_s(E_s, \chi) = C \cdot \frac{E_s}{(E_s + \chi)^3} \quad (8b)$$

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 20

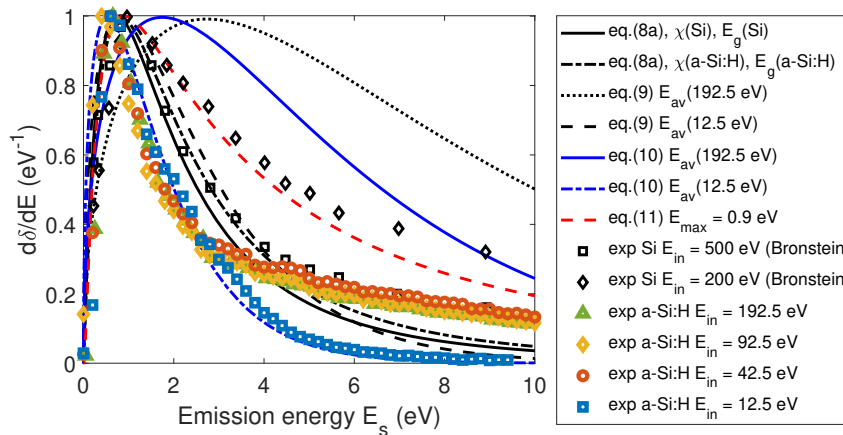


Figure 15: Measured secondary emission energy distribution compared to theoretical curves from literature for a-Si:H and Si.

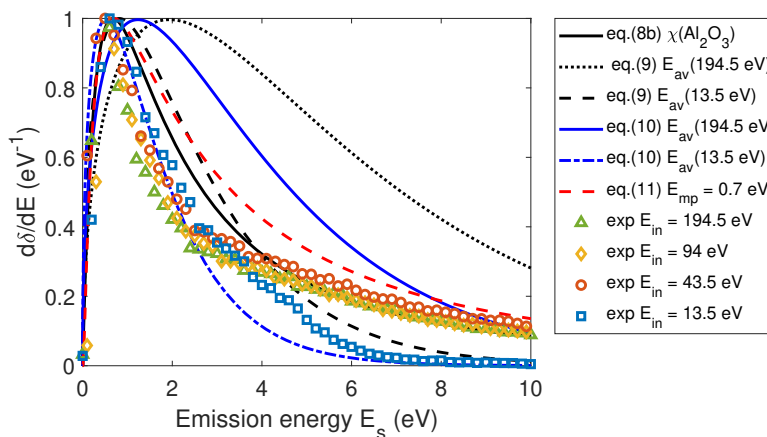


Figure 16: Secondary emission energy distribution compared to theoretical curves from literature for Al₂O₃.

for insulators, where χ is the electron affinity, E_g the band gap and C a normalization constant. We use the values listed in table 3 for χ and E_g . The model is based upon the assumption that the electrons are ejected from the valence band. Empirical secondary

Table 3: Electron affinity and band gap of Si, a-Si:H and Al₂O₃.

	Si	a-Si:H	Al ₂ O ₃
Electron affinity χ (eV)	3.2	3.92	1.35
Band gap E_g (eV)	1.12	1.8	7.0/7.6 Filatova and Konashuk (2015)

electron distribution functions are typically used for MCP modelling by Yakobson (1966); Price and Fraser (2001); Kruschwitz et al. (2011). All of these functions are phenomenological. The fit function by Yakobson (1966) is

1
2
3 *A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies* 21
4

$$5 \quad d\delta/dE_s(E_s, E_{av}) = C \cdot E_{av}^{-1.5} \cdot \sqrt{E_s} \exp\left(-1.5 \frac{E_s}{E_{av}}\right). \quad (9)$$

6
7
8 with the average emission energy E_{av} . We use $E_{av}(E_{in} = 12.5 \text{ eV}) = 2.5 \text{ eV}$ with
9 a normalization factor of $C = 5$ and $E_{av}(E_{in} = 192.5 \text{ eV}) = 8.2 \text{ eV}$ with $C = 22.9$.
10 Furthermore, we tested the fit function of Price and Fraser (2001)
11

$$12 \quad d\delta/dE_s(E_s, E_{av}) = 3.3 \cdot (E_s/E_{av})^{0.47} \cdot \exp(-2.21 \cdot E_s/E_{av}) \quad (10)$$

13 and the fit function of Kruschwitz et al. (2011)
14

$$15 \quad d\delta/dE_s(E_s, E_{mp}) = \exp\left(\frac{-(\log(E_s/E_{mp}))^2}{2 \cdot 1.33^2}\right) \quad (11)$$

16
17
18 with the most probable emission energy $E_{mp} = 0.9 \text{ eV}$. None of the theoretical curves
19 can represent the measured curves perfectly, as shown in figure 15. We found the best
20 fit with equations 11 and 8a for incident energies above 25 eV. Although the fit function
21 of the equation 10 may be appropriate for the energy spectrum at $E_{in} = 12.5 \text{ eV}$, it does
22 not hold for higher incident energies.
23

24 The low energy part of the Al₂O₃ spectra were compared to the theoretical
25 secondary electron distribution curves of Al₂O₃ in figure 16. Here, the best fit was
26 obtained with the theoretical curve of equation 8b for incident energies above 25 eV.
27 None of the functions could be used to represent the energy spectrum at $E_{in} = 13.5 \text{ eV}$.
28

29 For incident energies below 25 eV, the emission energy distributions of both
30 materials depend on the incident energy and cannot be represented by any of the
31 functions above. In this energy range we use an energy dependent fit function for
32 incident energies below 25 eV for a-Si:H and Al₂O₃ using an energy dependence proposed
33 for copper and stainless steel by Furman and Pivi (2002):
34

$$35 \quad \partial\delta/\partial E_s(E_{in}) = \frac{\Gamma((P_1 + P_2)/2) \cdot (P_1/P_2)^{P_1/P_2} \cdot E_s^{P_1/P_2 - 1}}{\Gamma(P_1/2) \cdot \Gamma(P_2/2) \cdot (1 + P_1/P_2 \cdot E_s)^{(P_1 + P_2)/2}} \quad (12)$$

36 where $\Gamma(x)$ is the Gamma function of x and x is an integer. In contrast to the original
37 interpretation of P_1 and P_2 as probabilities of emitting 1 or 2 electrons, respectively,
38 we consider these magnitudes as functions of the incident energies. The best fit was
39 obtained for $P_1 = 39 \cdot \exp(-E_{in}/68) + 111$ and $P_2 = 2$. The fit function is shown in
40 figure 17, where the resulting probability density function (PDF) is compared with the
41 measured secondary electron emission spectra of a-Si:H and Al₂O₃. In the same figure
42 we also present corresponding cumulative distribution functions, obtained by integration
43 of the PDFs, which are necessary for performing MC simulations of AMCPs.
44

45 From the energy distribution analysis in this chapter we derived a parameterization
46 for the energy dependence of elastic backscattering. While secondary emission energy
47 models from literature could represent the emission energy spectrum for high incident
48 energies, we found that at low incident energies, the electron energy spectrum depends
49
50
51
52
53
54
55
56
57
58
59
60

A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies 22

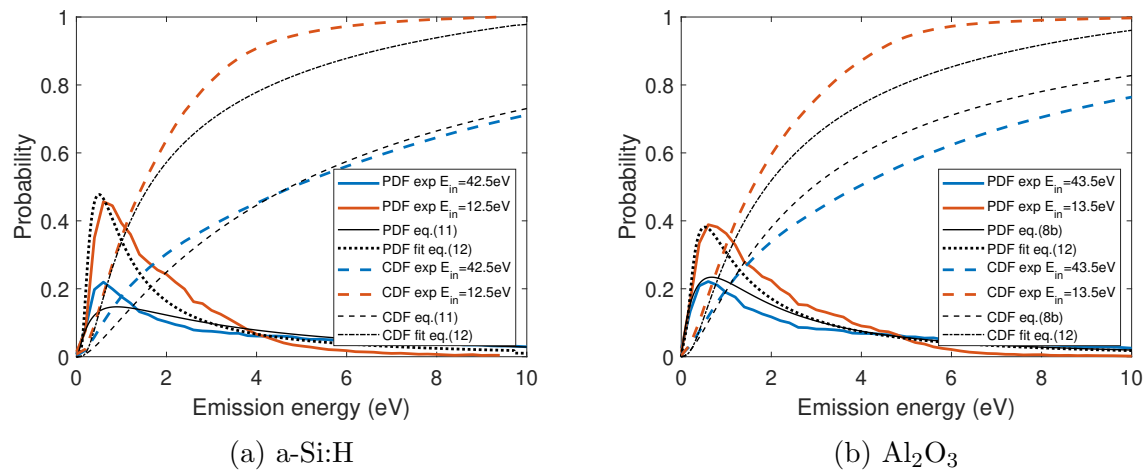


Figure 17: Probability density function (PDF) and cumulative distribution function (CDF) of the secondary electron emission energy for low primary electron energies E_{in} and their fit functions.

on the incident energy. Finally, we showed a suitable parameterization for the energy emission spectrum of both a-Si:H and Al₂O₃ using equation 12 at low incident energies.

4. Conclusion

In this paper, we provide a complete analysis of electron emission characteristics, which is necessary for reliable AMCP modelling. The electron emission energy distribution and the emission yield of a-Si:H and Al₂O₃ with two different surface textures have been characterized at low incident electron energies. A comparison to literature values confirmed the need for this detailed analysis, as there are significant variations between measurements, analytical expressions and Monte Carlo models. Furthermore, we defined parametrizations for the expected electron scattering process depending on the incident electron energy and determined analytical functions describing the energy dependence of the secondary electron energy distribution.

In general, amorphous silicon shows a higher emission yield than crystalline silicon which has a maximum yield below 1.2. The average emission yield of a-Si:H is about 1.6, deduced by Franco et al. (2014) from the operation of AMCPs. In the present study, a rough surface leads to a further increase of the electron emission yield of amorphous silicon up to a maximum of approximately 1.6 at normal and of 2 at 75 degree incidence. Curvature and trenches in a microchannel modify the actual surface texture in the channel and therefore influence the emission yield and the crossover energy such that it cannot be reconstructed based on thin film measurements. In addition, the local electric field strength in AMCP channels under operation can modify the secondary emission yield. Together with electron incidence at grazing angles, this could be the reason for the effective emission yield of 1.6 observed so far in AMCPs.

1
2
3 *A comprehensive analysis of electron emission from a-Si:H/Al₂O₃ at low energies* 23
4

5 Since coatings with highly emissive ALD films are the key to improve the potentially
6 high gain achievable with AMCPs, we explored the low energy electron emission
7 properties of ALD-deposited Al₂O₃. We measured a maximum emission yield of up
8 to 2.8. The TEY of Al₂O₃ can be further increased by increasing the film thickness.
9 Yield values up to 3.5 were measured and theoretic models by van der Graaf et al. (2017)
10 predict even higher electron yields.
11

12 We determined the energy and angular dependencies of the emission energy
13 distribution for a-Si:H and Al₂O₃. In accordance with literature, the probability for
14 elastic backscattering is high at low incident energies. For incident energies below 25
15 eV, the secondary emission spectrum depends on the incident energy, which is not the
16 case for higher incident energies. For electron multiplication processes at these low
17 energies, such as in AMCPs, this emission energy variation needs to be considered.
18

19 With the present analysis, the determining factors of electron emission at low
20 energies in a-Si:H were identified and extended for Al₂O₃. The angular dependence and
21 energy dependence of the electron emission yield and energy distribution are therefore
22 understood and can be used for more detailed modelling and thus further development of
23 electron multipliers. This can be particularly relevant for developing electron multipliers
24 that deviate from the cylindrical shape of microchannels.
25

26 This study could also be extended to other highly emissive layers that can be
27 deposited via ALD, such as MgO, Ti doped MgO or multi layered structures as indicated
28 by Tao et al. (2016). With a maximum yield of more than 10 for an 11 nm layer
29 measured by Jokela et al. (2011), MgO has a real potential to tremendously improve
30 AMCP performance and could enable them to reach a multiplication factor well above
31 10⁵.
32
33
34
35
36
37

38 **5. Acknowledgements**

39

40 We are grateful to Philippe Wyss for deposition of the flat a-Si:H layers, Mohammad
41 Beygi for AFM imaging and Pierre Mettraux for the XPS analysis of the flat Al₂O₃
42 layer. Results presented here were obtained with the financial support of the Swiss
43 National Science Foundation project 200021_162525/1, the Swiss National Science
44 Foundation through the Sinergia program (Grant No. 177165, 2018–2022) and the
45 Portuguese National Funding Agency for Science, Research and Technology in the
46 framework of the project CERN/FIS-TEC/0039/2019 and the grants UIDB/00068/2020
47 and UIDP/00068/2020.
48

49 The authors have no conflicts of interest to declare.
50
51
52
53
54
55
56
57
58
59
60

REFERENCES

24

References

- Andronov A, Smirnov A, Kaganovich I, Startsev E, Raitses Y and Demidov V 2013 *AIP Conf. Proc. C* **1206051**, 161–163. 3 p. Comments: 3 pages, contribution to the Joint INFN-CERN-EuCARD-AccNet Workshop on Electron-Cloud Effects: ECLOUD'12; 5-9 Jun 2012, La Biodola, Isola d'Elba, Italy.
URL: <http://cds.cern.ch/record/1601946>
- Balcon N, Payan D, Belhaj M, Tondu T and Inguibert V 2012 *IEEE Transactions on Plasma Science* **40**(2 PART 1), 282–290.
- Belhaj M, Tondu T, Inguibert V, Barroy P, Silva F and Gicquel A 2010 *Journal of Physics D: Applied Physics* **43**(13).
- Blayo N and Drévillon B 1992 *Surface Science* **260**(1), 37–43.
URL: <https://www.sciencedirect.com/science/article/pii/003960289290016Y>
- Bronshtein I M and Fraiman B S 1969.
- Bundaleski N, Belhaj M, Gineste T and Teodoro O M 2015 *Vacuum* **122**, 255–259.
URL: <http://dx.doi.org/10.1016/j.vacuum.2015.04.010>
- Cauchy L 1830 *bull. des. sc. maht.* **14**, 9.
- Cazaux J 2010 *Ultramicroscopy* **110**(3), 242–253.
URL: <http://dx.doi.org/10.1016/j.ultramic.2009.12.002>
- Cazaux J 2012 *Journal of Applied Physics* **111**(6), 064903.
URL: <http://aip.scitation.org/doi/10.1063/1.3691956>
- Cimino R, Collins I R, Furman M A, Pivi M, Ruggiero F, Rumolo G and Zimmermann F 2004 *Physical Review Letters* **93**(1), 014801–1.
- Cimino R, Gonzalez L A, Larciprete R, Di Gaspare A, Iadarola G and Rumolo G 2015 *Phys. Rev. ST Accel. Beams* **18**, 051002.
URL: <https://link.aps.org/doi/10.1103/PhysRevSTAB.18.051002>
- Demers H, Poirier-Demers N, Couture A R, Joly D, Guilmain M, de Jonge N and Drouin D 2011 *Scanning* **33**(3), 135–146.
URL: <http://doi.wiley.com/10.1002/sca.20262>
- Elam J W, Xiong G, Han C Y, Wang H H, Birrell J P, Welp U, Hryn J N, Pellin M J, Baumann T F, Poco J F and Satcher J H 2006 *Journal of Nanomaterials* **2006**, 1–5.
- Filatova E O and Konashuk A S 2015 *The Journal of Physical Chemistry C* **119**(35), 20755–20761. Publisher: American Chemical Society.
URL: <https://doi.org/10.1021/acs.jpcc.5b06843>
- Fitting H J, Schreiber E, Kuhr J C and von Czarnowski A 2001 *Journal of Electron Spectroscopy and Related Phenomena* **119**(1), 35–47.
URL: [https://doi.org/10.1016/S0368-2048\(01\)00232-8](https://doi.org/10.1016/S0368-2048(01)00232-8)
<https://linkinghub.elsevier.com/retrieve/pii/S0368204801002328>
- Franco A 2014.
URL: <http://infoscience.epfl.ch/record/200863>

REFERENCES

25

- Franco A, Geissbühler J, Wyrsh N and Ballif C 2014 *Scientific Reports* **4**(August 2015), 1–7.
URL: <http://www.nature.com/doi/finder/10.1038/srep04597>
- Frey S, Löffler J, Ballif C and Wyrsh N 2019 in ‘2019 IEEE Nuclear Science Symposium and Medical Imaging Conference, NSS/MIC 2019’ Institute of Electrical and Electronics Engineers Inc.
- Furman M A and Pivi M T 2002 *Physical Review Special Topics - Accelerators and Beams* **5**(12), 82–99.
- Guo J, Wang D, Xu Y, Zhu X, Wen K, Miao G, Cao W, Si J, Lu M and Guo H 2019 *AIP Advances* **9**(9), 095303.
URL: <https://doi.org/10.1063/1.5113671>
- Henke B L, Liesegang J and Smith S D 1979 *Physical Review B* **19**(6), 3004–3021.
- Ivanov V, Barnyakov A and Barnyakov M 2018 *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **903**(June), 170–174.
URL: <https://doi.org/10.1016/j.nima.2018.05.046>
- Jablonski A 2014 *Journal of Physics D: Applied Physics* **47**(5).
- Jokela S J, Veryovkin I V, Zinovev A V, Elam J W, Mane A U, Peng Q and Insepov Z 2012 *Physics Procedia* **37**, 740–747.
URL: <http://linkinghub.elsevier.com/retrieve/pii/S1875389212017567>
- Jokela S J, Veryovkin I V, Zinovev A V, Elam J W, Peng Q and Mane A U 2011 *AIP Conference Proceedings* **1336**, 208–212.
- Joy D and Luo S 1989 *Scanning* **11**(4), 176–180.
- Kieft E and Bosch E 2008 *Journal of Physics D: Applied Physics* **41**(21).
- Kruschwitz C A, Wu M and Rochau G A 2011 *Review of Scientific Instruments* **82**(2).
- Kuhr J C and Fitting H J 1999 *Journal of Electron Spectroscopy and Related Phenomena* **105**(2-3), 257–273.
- Ladislav Wiza J 1979 *Nuclear Instruments and Methods* **162**(1-3), 587–601.
URL: <http://linkinghub.elsevier.com/retrieve/pii/0029554X79907341>
- Löffler J, Thomet J, Belhaj M, Kessel L V, Hagen C W, Ballif C and Wyrsh N 2019 *IEEE Nucl. Sci. Symp. Conf. Rec.* pp. 1–6.
URL: <https://ieeexplore.ieee.org/document/9059971>
- Löffler J, Ballif C and Wyrsh N 2018 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **912**, 343–346.
URL: <https://linkinghub.elsevier.com/retrieve/pii/S0168900217314262>
- Nečas D and Klapetek P 2012 *Central European Journal of Physics* **10**, 181–188.
- Pierron J, Inguibert C, Belhaj M, Gineste T, Puech J and Raine M 2017 *Journal of Applied Physics* **121**(21).
URL: <https://doi.org/10.1063/1.4984761>

REFERENCES

26

Price G J and Fraser G W 2001 *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **474**(2), 188–196.

Salvat F, Jablonski A and Powell C J 2005 *Computer physics communications* **165**(2), 157–190.

Schulte S, Hartung G, Kröger J, Himmerlich M, Petit V and Taborelli M 2020 *Physical Review Accelerators and Beams* **23**(10), 103101.

URL: <https://doi.org/10.1103/PhysRevAccelBeams.23.103101>

Shih A, Yater J, Hor C and Abrams R 1997 *Applied Surface Science* **111**, 251–258.

Tao S X, Chan H W and Van der Graaf H 2016 *Materials* **9**(12).

URL: <https://www.mdpi.com/1996-1944/9/12/1017>

Tao S X, Theulings A, Smedley J and Van Der Graaf H 2015 *Diamond and Related Materials* **53**, 52–57.

van der Graaf H, Akhtar H, Budko N, Chan H W, Hagen C W, Hansson C C, Nützel G, Pinto S D, Prodanović V, Raftari B, Sarro P M, Sinsheimer J, Smedley J, Tao S, Theulings A M and Vuik K 2017 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **847**(November 2016), 148–161.

URL: <http://linkinghub.elsevier.com/retrieve/pii/S0168900216312311>

van Kessel L and Hagen C W 2020 *SoftwareX* **12**, 100605.

URL: <https://doi.org/10.1016/j.softx.2020.100605>

Vaughan J R M 1989 *IEEE Transactions on Electron Devices* **36**(9), 1963–1967.

Villemant M, Sarrailh P, Belhaj M, Garrigues L and Boniface C 2017 *Journal of Physics D: Applied Physics* **50**(48), aa91af.

URL: <https://doi.org/10.1088/1361-6463/aa91af>

Yakobson A M 1966 *Radiotekhnika i Elektronika* **11**, 1813–1823.