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Design of a HAADF Detector for Z Contrast in SEM

Gilles L'Espérance[1], Jean-Paul Baïlon[1], Olivier Sioui-Latulipe[1], John Hunt[2] and Sander Gubbens[2]

[1.] Ecole Polytechnique, (CM)[2], Montréal (QC) H3C 3A7 Canada.
[2.] Gatan Inc., 5794 W Las Positas Blvd, Pleasanton, CA USA.

In (S)TEM, the use of HAADF detectors to acquire images of thin foils for which the contrast arises from differences in chemical composition (Z contrast) is well known [1]. In the SEM, however, such Z contrast detectors, capable of precise angular adjustment and quantitative detection, are not available to our knowledge. The objective of the work presented here is to design such a HAADF detector that can be used in the SEM to observe Z contrast in a thin foil. In the case of crystalline materials, the design of the detector must be such that strongly diffracted beams are not collected.

To setup the detector for SEM operation at 30 kV, it is necessary to first determine the Bragg angles, θ, of the possible diffracting planes. Applying Bragg's law to the most compact planes ({111}, {200}, {220}, {311}, {222}) of the main FCC metals (e.g., Al, Ni, Cu, Au) and the ({110}, {200}, {220}, {211}, {310}) planes of the main BCC metals (e.g., Fe, Cr, Mo, W), we find that the maximum Bragg angle, θ_{max}, is typically less than 6°, even for the third order of diffraction. It follows that the HAADF detector must not detect electrons diffracted in a cone having a semi-angle equal to $2\theta_{max} = 12°$. A schematic of the detector is shown in figure 1. The diameter Φ of the central hole will depend on DD, the distance between the thin foil and the detector ($\Phi = 2DD. \tan(2\theta_{max})$). Below the central hole is a detector that will allow collection of electrons scattered within the cone having a semi-angle of $2\theta_{max}$. It will therefore allow collection of the transmitted and diffracted electrons in the case of a crystalline sample.

In order to evaluate the sensitivity of the proposed detector for Z contrast, software to model the trajectories of primary electrons in a solid was used [2]. A theoretical sample made of a 100nm thin foil of the material of interest (with atomic number **Z**) is analyzed with 30 keV electrons (figure 2). To allow the software to visualize the trajectories of the electrons in the space beyond the foil, the space was simulated to be filled with hydrogen (a very weak scattering element). By counting the percentage **β** of the electrons exiting the thin foil outside the cone with a semi-angle $2\theta_{max} = 12°$ at the apex, one can determine the dependence of this percentage **β** on the atomic number **Z** of the thin foil (figure 3). The large variation of **β** with **Z** shows that images with a very good Z contrast should be possible with the HAADF detector proposed.

As shown in figure 1, the detector is made of a HAADF detector (for Z contrast) associated with a small inner detector (for imaging diffraction contrast from crystalline samples). Table 1 summarizes the different types of contrast possible from images obtained with: a) the HAADF detector, b) the inner detector and c) by adding the signals from the two detectors. Finally, it is possible to estimate the current reaching the detector using the following assumptions:

$\mathbf{I_p}$ = beam current; $\mathbf{I_T}$ = transmitted current = $\mathbf{TI_p}$ with **T** = transmission coefficient of the thin foil;

T = **(1 - η)** with **η** the backscattering coefficient of the thin foil as given by CASINO simulations;

ε = the collection efficiency of the HAADF detector (**ε** < 1 since the HAADF detector has a finite external diameter and a small internal diameter inactive area). With these definitions, the following equations can be deduced:

Current inside the inner cone (detected by the lower small detector) : $\mathbf{I_{IC} = (1-\beta)I_T = (1-\beta)TI_p}$ (eq. 1)
Current outside the inner cone (detected by the HAADF detector) : $\mathbf{I_{OC} = \varepsilon\beta I_T = \varepsilon\beta TI_p}$ (eq. 2)
Total current reaching the two detectors : $\mathbf{I_{IC} + I_{OC} = (1-\beta+\varepsilon\beta)TI_p}$ (eq. 3)
Assuming a beam current of $\mathbf{I_p}$ = 1 nA and a collection efficiency of $\boldsymbol{\varepsilon}$ = 80%, the values calculated for $\mathbf{I_{IC}}$ and $\mathbf{I_{OC}}$ are given in table 2. The calculations clearly show that the proposed HAADF detector should result in images with excellent Z contrast for thin foils with a thickness of 100 nm. The proposed detector is currently being built and results obtained with the detector will be presented.

References:
[1] D.B. Williams and C.B. Carter in "Transmission Electron Microscopy", ed. Plenum Press, 1996, volume **III** "Imaging", p. 358-361.
[2] CASINO, V 2.4.8., http://www.gel.usherbrooke.ca/casino/what.html.

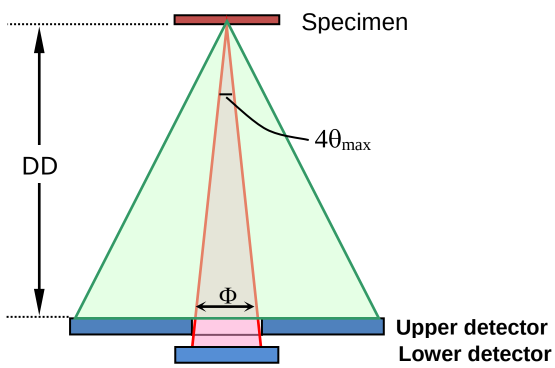

Figure 1. Schematic of the proposed detector.

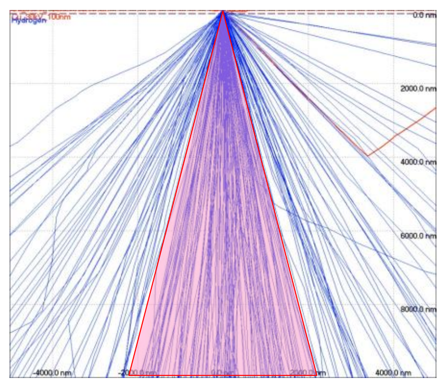

Figure 2. Trajectories of the transmitted electrons outside a thin foil (100 nm) of copper (Z = 29).

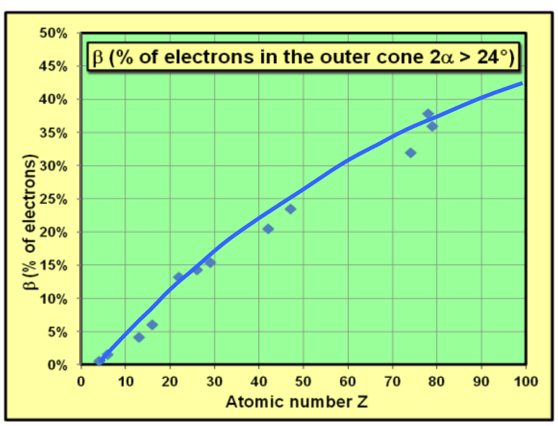

Figure 3. The dependence of β vs Z

	Specimen	
	Crystalline	Amorphous
Upper detector	Z contrast	Z contrast
Lower detector	Diffraction contrast + Inverted Z contrast	Inverted Z contrast
Upper + Lower detectors	Diffraction contrast + Inverted Z contrast	Inverted Z contrast

Table 1. Types of contrast possible with the detector

Element	**Z**	$\mathbf{I_{IC}}$ (nA)	$\mathbf{I_{OC}}$ (nA)	$\mathbf{I_{IC} + I_{OC}}$ (nA)
Al	13	0.957	0.027	0.984
Au	79	0.508	0.228	0.736
Detector	--	Lower	Upper	Upper + Lower
Contrast	--	Inverted	Normal	Inverted

Table 2. Values of the currents reaching the HAADF detector and the inner detector

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