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SECONDARY ELECTRON EMISSION: PROGRESS AND PROSPECTS

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Abstract

This article updates the paper "Secondary Electron Emission from Solids by Electron and Proton Bombardment" published in Scanning Microscopy Vol. 2, pages 607–632 (1988). The recent development in secondary electron emission from solids by electron or proton bombardment is reviewed. The similarities between electron- and ion-induced emission are emphasized. Recent theoretical results for the emission from beryllium agree well with existing experimental results. Results from new directions are included in the discussion.

Key Words: Electron-induced secondary electron emission, proton-induced secondary electron emission, stopping power, comparisons between primary protons and electrons, transport theory.

There have been recent developments in the field of secondary electron emission from solids primarily in the collection of experimental basic data and in working out theoretical treatments rather than in Monte-Carlo simulations and in extending the work into new areas.

A major element in the current understanding of electron emission is the realization that secondary electron emission induced by electrons is closely connected to that induced by fast protons. The inclusion of both kinds of primary particles in a single theoretical treatment was first done systematically by the present author (Schou (1980a,b)). However, as early as 1941 Bethe (1941) did not distinguish between electron- and ion-induced emission. Rösler and Brauer (1981, 1984, 1988) as well as Dubus et al. (private communication) included both primaries in their theoretical treatments. The common aspects of secondary electron emission from primary electrons and protons were incorporated also in recent reviews on electron emission during ion bombardment (Sigmund and Tougaard (1981), and Hasselkamp (1985)). The reason for the similarity of the emission induced by the two different particles is that the important physical quantities, the stopping power, ionization cross section and excitation cross section are practically identical for protons and electrons of the same velocity (Schou (1988)). Once, the electrons are liberated as a result of the interaction with the primary, their motion and escape through the surface are independent of the primary.

As a result of the comprehensive work by Hasselkamp and coauthors the data basis for ion-induced emission has been extended far beyond the previous stage. Their work has been summarized in Hasselkamp (1985), Hasselkamp et al. (1987) and Hippler et al. (1988). The metals investigated range from the nearly free electron metals aluminium and beryllium to the noble metals and some transition metals, as, for example, titanium. The secondary electron yield was measured on well-characterized surfaces, which were cleaned by argon ion sputtering of energy typically about 500 keV. The energy region studied was essentially from 100 keV to 1 MeV. The data reduce the gap between the results from Svensson and Holmen (1981) obtained with energies up to 400 keV and those from Koyama et al. (1981) at and above 4 MeV. In addition, most of Hasselkamp's measurements of proton-induced emission were carried out at primary energies above the position of the stopping power maximum. It means that inner-shell effects scarcely play a role in producing internal secondaries; i.e., the secondaries are generated when conduction electrons in metals are excited or the outermost shell for insulators is ionized (see the discussion in Schou (1988)). The yield for protons incident on beryllium throughout the energy range is shown in Fig. 1.

The data from Hasselkamp and coauthors confirm the conclusions from other groups that the secondary electron yield δ during proton bombardment is almost directly proportional to the stopping power (Schou (1988)). Furthermore, the comprehensive data sets demonstrated that the constant of proportionality, $\delta/|dE/dx|_e$, depends on the metal, although the variation is about a factor of 2 from 0.0067 nm/eV for titanium up to 0.013 nm/eV for silver. The tabulations of Andersen and Ziegler (1977) were used for the electronic stopping power $(dE/dx)_e$. This difference reflects the individual properties of the metals such as the magnitude of the work function Φ, the Fermi energy E_F and the stopping power of the migrating low-energy electrons.

Hasselkamp and coauthors did not only produce secondary electron yields for a number of metals, but energy spectra of the emitted electrons as well. This is the first comprehensive analysis of the shape of the spectra for many materials measured at the *same set up* (Hasselkamp (1985) and Hasselkamp et al. (1987)). It turned out that the position of the maximum in the spectra varied from 1.8–2.0 eV (Si and Al) up to 3.8 eV (Nb). The full-width at half-maximum changed from 6.0 eV (Mg) up to 11.8 eV (Ti). These results contradict the conventional expectation that the shape of the energy spectrum is independent of the metal, in particular for electron-induced emission. This latter point of view has survived primarily because electron-induced spectra from very few metals were available. It means that the data are certainly not representative of all metals. For aluminium, which more or less has become a standard material, the agreement in shape between the spectra from ion bombardment (Hasselkamp et al. (1987)) and electron bombardment (Roptin (1975)) is good. The half-widths obtained by Bindi et al. (1979) are systemically about 25% lower for aluminium, copper and the noble metals.

Aluminium has become a standard material for the theoretical treatments as well. The reason is that the many existing experimental results stimulated calculations for aluminium which is a simple, nearly-free-electron metal. The initial evaluations of inelastic cross sections by Ganachaud and Cailler (1979a and 1979b) and the stopping power and inelastic mean-free-path calculations by Tung and Ritchie (1977) and Ashley et al. (1979) were followed by evaluations of yield and spectra from Schou (1980a,b and 1988), Rösler and Brauer (1981, 1984 and 1988), Bindi et al. (1987) and Dubus et al. (1987 and private communication). Except for Schou's work, these results are based on refined methods for solving the forward Boltzmann equation. Usually, the calculations have been so complex that the results have been presented in the form of curves rather than in analytical terms. However, the recent treatment by Devooght et al. (1987) based on this Boltzmann equation has demonstrated that it is possible to reach analytical expressions that explicitly demonstrate the dependence on the important physical quantities. They even succeeded in reproducing analytical results from early theories and found the same dependence on the low-energy electron stopping power for the energy spectra as Schou (1980a).

The results of Schou's original treatment has been extended to comprise the nearly-free-electron metals beryllium and magnesium (Schou (1988)). In this model the secondary electron yield δ produced by electrons of energy E for normal incidence is expressed as:

$$\delta = D(E,0,1)\Lambda \qquad (1)$$

where $D(E,x,\cos\theta)dx$ is the energy that is deposited ultimately in electron excitation in the depth interval $[x,x+dx]$ by a primary particle with angle θ of incidence. Λ is a material-dependent parameter which depends on the magnitude of the components Φ and E_F of the surface energy barrier $U_0 = \Phi+E_F$ and, as mentioned above, on the stopping power $|dE_0/dx|$ of the low-energy electrons of energy E_0:

$$\Lambda = (c/4) \int_{U_0}^{\infty} dE_0(1-U_0/E_0)/(E_0|dE_0/dx|) \qquad (2)$$

For details the reader is referred to Schou (1980a and 1988) (e.g., p. 2161 in Schou (1980a)). The surface value (x=0) of the deposited electronic energy incorporates the dependence on the type of primary particle. One obtains:

$$D(E,0,\cos\theta) = \beta|dE/dx|_e \qquad (3)$$

where β is a dimensionless constant ($\cos\theta = 1$) which is different for protons and electrons (Table 2 in Schou (1988)). The expression in Eq. (1) is derived under the assumption that the majority of internal secondaries result from cascade multiplication processes. It means that the theory is inapplicable at primary energies that are too low. In Fig. 1, data from Hasselkamp (1985) for beryllium are compared with the values calculated from Eq. (1) by means of Table 2 in Schou (1988) and the proton stopping power from Andersen and Ziegler (1977). Similar data for primary electrons from Bronshtein and Fraiman (1961) and Bronshtein and Denisov (1965) are shown in Fig. 2. One notes that the shape of the theoretical curve in both cases agrees well with the experimental data, and that the absolute agreement is fair for the highest primary energies.

This treatment is based on an analogy to sputtering theory (Sigmund (1981)). The appearance of the low-energy electron stopping power (dE_0/dx) in the denominator of Eq. (2) is a characteristic feature of the theory, but other authors have also demonstrated this dependence, e.g., Bethe (1941), Sigmund and Tougaard (1981), and, as mentioned above, Devooght et al. (1987). By this procedure one avoids including any mean-free-path or characteristic diffusion length for the migrating low-energy electrons (Schou (1988)).

The inclusion of *other* nearly-free-electron metals is a straightforward extension of all the theories mentioned here, but predictions for the noble and transition metals would also be desirable. The current activity in the field indicates that these results may appear relatively soon.

With regard to *experimental results*, systematic data for electron-induced electron emission from well-characterized surfaces are desirable. In particular, electron spectra and yields from transition metals, for example titanium and niobium at primary energies from 2 up to perhaps 20 keV, would be useful for making comparisons with the data from ion-induced emission. The amount of data from ion bombardment is encouraging, but secondary electron yields from other energy regimes would be interesting as well. Recently, Borovsky et al. (1988) extended the proton energy regime up to 18 MeV, and obtained a fair agreement with the high-energy data from Koyama et al. (1981).

The field of secondary electron emission *from insulators* has been neglected apart from a few studies, for example by Croitoru et al. (1988). The application of sputtering for film deposition and sample cleaning is expected to stimulate the interest in this relatively unexplored field. It will be exciting to compare new data with the large amount obtained more than twenty years ago.

The application of *spin polarization* analysis leads to a promising technique for surface studies of magnetic materials (Kirschner 1989)). In the author's opinion, this method has and will provide us with important results about the primary excitation mechanism.

Data from *monoenergetic* low-energy *positron* beams are expected to lead to a new interesting area of particle-induced electron emission. The first comparative study indicates that the positron-induced electron emission is larger than the corresponding electron-induced one for nickel, silicon and magnesium oxide. The important feature by the positron measurements is that the backscattered primaries with exit energy below 50 eV are not included in the secondary electron yield.

Many methods for surface analysis require that the background of secondary electrons in the spectra has to be subtracted. One of the few recent Monte-Carlo calculations (Ding and Shimizu (1988)) has included the generation of secondaries in gold, copper, and silicon.

The recent studies on electron emission as a result of ion bombardment have led to an appreciable number of new data for a variety of primary ions (Ferguson and Hofer (1989) and Lakits et al. (1989)). Although the production process for the secondary electrons by heavy keV ions differs from the production process by MeV-keV protons and keV electrons, some features, e.g., the escape, are similar for these primary particles.

Finally, the incorporation of *secondary electron spectroscopy* in the surface characterization as a reliable supplement to other methods demands a large experimental data base and comprehensive theoretical results. Recent studies by Burkhard et al. (1987 and 1988) and Woods et al. (1987) demonstrate that the influence of contaminants and implanted particles has to be included in future work on secondary electron emission from electron or proton impact.

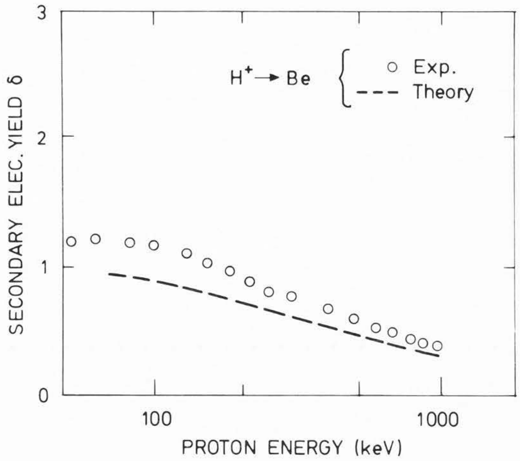

Fig. 1. The secondary electron yield δ from proton bombardment depicted versus the primary energy. o, experimental results from Hasselkamp (1985). --, theory, Eq. (1) with values from Table 2 in Schou (1988). (β = 0.275 and Λ = 0.029 nm/eV).

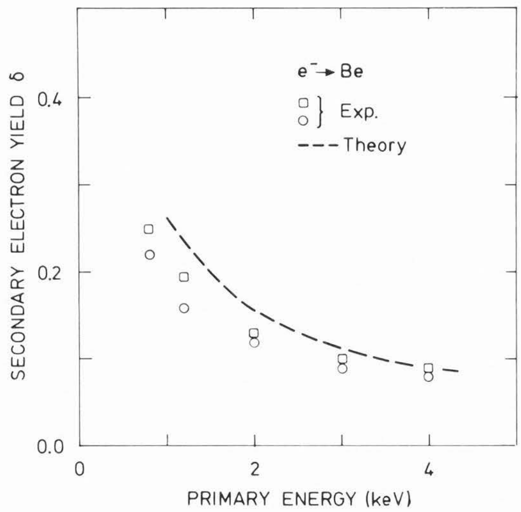

Fig. 2. The secondary electron yield δ from electron bombardment is depicted versus the electron energy. Experimental results, □, Bronshtein and Denisov (1965), o, Bronshtein and Fraiman (1961), --, theory Eq. (1) with values from Table 2 in Schou (1988). (β = 0.5 and Λ = 0.029 nm/eV).

References

Andersen HH, Ziegler JF. (1977). Hydrogen stopping powers and ranges in all elements (Pergamon, New York), 1–317.

Ashley JC, Tung CJ, Ritchie RH. (1979). Electron inelastic mean free paths and energy losses in solids. I. Aluminium metal, Surf. Science **81**, 409–426.

Bethe HA. (1941). On the theory of secondary emission, Phys. Rev. **59**, 940.

Bindi R, Lanteri H, Rostaing P. (1979). Distributions energetiques experimentales des electrons secondaires emis par des cibles evaporees d'aluminium, de cuivre, d'or et d'argent. J. Electr. Spectr. Rel. Phen. **17**, 249–258.

Bindi R, Lanteri H, Rostaing P. (1987). Secondary electron emission by reflection induced by electron bombardment of polycrystalline metallic targets, Scanning Microscopy **1(4)**, 1475–1490.

Borovsky JE, McComas DJ, Barraclough BL. (1988). The secondary-electron yield measured for 5–24 MeV protons on aluminium-oxide and gold targets. Nucl. Instr. Meth. **B30**, 191–195.

Bronshtein IM, Fraiman BS. (1961). Inelastic scattering of electrons and secondary electron emission from certain metals and semiconductors. Sov. Phys. Solid State **3**, 1188–1196.

Bronshtein IM, Denisov SS. (1965). Study of secondary electron emission from solids with obliquely incident primary electrons, Sov. Phys. Solid State **7**, 1484–1491.

Burkhard M, Rothard H, Biedermann C, Kemmler J, Koschar P, Groeneveld KO. (1987). Strong convoy electron yield dependence on surface properties, Nucl. Instr. Meth. **B 24–25**, 143–146.

Burkhard M, Rothard H, Kemmler J, Kroneberger K, Groeneveld KO. (1988). Surface characterisation of thin solid foil targets by ion impact. J. Phys. **D 21**, 472–477.

Croitoru N, Seidman A, Yassin K. (1988). Secondary electron emission of ZnO sputtered films. Phys. Scripta **37**, 555–558.

Devooght J, Dubus A, Dehaes JC. (1987). Improved age-diffusion model for low-energy electron transport in solids. I Theory. Phys. Rev. **B36**, 5093–5109.

Ding ZJ, Shimizu R. (1988). Monte Carlo study of backscattering and secondary electron generation. Surf. Science **197**, 539–554.

Dubus A, Devooght J, Dehaes JC. (1987). Improved age-diffusion model for low-energy electron transport in solids. II Application to secondary emission from aluminium. Phys. Rev. **B 36**, 5110–5119.

Ferguson MM, Hofer WO. (1989). Ion-induced kinetic electron emission from metals, Rad. Effects. Def. Solids (in press).

Ganachaud JP, Cailler M. (1979a). A Monte-Carlo calculation of the secondary electron emission of normal metals. Surf. Science **83**, 498–518.

Ganachaud JP, Cailler M. (1979b). A Monte-Carlo calculation of the secondary electron emission of normal metals. Results for aluminium. Surf. Science **83**, 519–530.

Hasselkamp D. (1985). Die ioneninduzierte Kinetische Elektronen-emission von Metallen bei Mittleren und Grossen Projektil-energien, University of Giessen-Habilitationsschrift, Giessen.

Hasselkamp D, Hippler S. Scharmann A. (1987). Ion-induced secondary electron spectra from clean metal surfaces. Nucl. Instr. Meth. **B 18**, 561–565.

Hippler S, Hasselkamp D, Scharmann A. (1988). The ion-induced electron yield as a function of target material, Nucl. Instr. Meth. **B 34**, 518–520.

Kirschner J. (1989). Spin-polarized secondary electrons from ferromagnets, In: Study of Surfaces and Interfaces by Electron Optical Techniques, Howie A, Valdrè V (eds.), Nato ASI series volume (in press).

Koyama A, Shikata T. Sakairi H. (1981). Secondary electron emission from Al, Cu, Ag and Au metal targets under proton bombardment, Jap. J. Appl. Phys. **20**, 65–70.

Lakits G, Aumayr F, Winter H. (1989). Statistics of potential electron emission, Rad. Effects Def. Solids (in press).

Roptin D. (1975). Etude experimentale de l'emission electronique secondaire de l'aluminium et de l'argent, Thesis, University of Nantes, Nantes.

Rösler M, Brauer W. (1981). Theory of secondary electron emission II. Application to aluminium, Phys. Stat. Sol. **b 104**, 575–587.

Rösler M, Brauer W. (1984). On the theory of ion-induced electron emission. Phys. Stat. Sol. **b 126**, 629–642.

Rösler M, Brauer W. (1988). Theory of electron induced emission from solids by proton and electron bombardment, Phys. Stat. Sol. **b 148**, 213–226.

Schou J. (1980a). Transport theory for kinetic emission of secondary electrons from solids, Phys. Rev. **B 22**, 2141–2174.

Schou J. (1980b). Transport theory for kinetic emission of secondary electrons from solids by electron and ion bombardment, Nucl. Instr. Meth. **170**, 317–320.

Schou J. (1988). Secondary electron emission from solids by electron and proton bombardment. Scanning Micr. **2**, 607–632.

Sigmund P. (1981). Sputtering by ion bombardment: Theoretical concepts. In: Sputtering by Particle Bombardment I, Behrisch R. (ed.), Springer, Berlin-Heidelberg, 9–71.

Sigmund P, Tougaard S. (1981). Electron emission from solids during ion bombardment. Theoretical aspects. In: Inelastic Particle-Surface Collisions, Taglauer E, Heiland W. (eds.), Springer, Berlin-Heidelberg, 2–37.

Sternglass EJ. (1957). Theory of secondary electron emission by high-speed ions. Phys. Rev. **108**, 1–12.

Svensson B, Holmén G. (1981). Electron emission from ion-bombarded aluminium, J. Appl. Phys. **52**, 6928–6933.

Tung CJ, Ritchie RH. (1977). Electron slowing-down spectra in aluminium metal, Phys. Rev. **B 16**, 4302–4313.

Woods ME, Hopkins BJ, Matthews GF, McCracken GM, Sewell PM, Fahrang H. (1987). An investigation of the secondary-electron emission of carbon samples exposed to a hydrogen plasma. J. Phys. **D 20**, 1136–1142.

Discussion with Reviewers

R. Bindi: Do experimental data or semi-empirical treatments lead to a "Universal yield curve" for proton-induced secondary electron emission?

Author: One may as well introduce a universal yield curve for proton-induced electron yields. I expect that such a yield curve will reproduce the experimental data just as well as does the corresponding universal curve for electron-induced secondary electron emission (see Fig. 12 in Schou (1988)). Nevertheless, such a curve shows merely that the stopping powers of all materials for protons are similar. Indeed, most of the existing theories for proton incidence indicate that the yield is proportional to the stopping power. One extreme case is the well-known semi-empirical theory of Sternglass (1957). He arrived at the result that the yield was proportional to the stopping power and entirely independent of the target material. Actually, the poor vacuum at that time led to experimental results that were practically independent of the material.

R. Bindi: Could you say something about the practical information resulting from comparison between proton and electron induced secondary electron-emission with the same primary particle velocity; e.g., about the various contributions in producing internal secondaries.

Author: For projectiles of the same velocity the production cross section for internal secondaries is similar, cf. the discussion in Sect. III of Schou (1988).

A. Dubus: Except for your work, the most recent theoretical calculations are mostly dedicated to incident electrons (calculations for H^+ ions from Rösler and Brauer (1984) and Dubus et al. (personal communications) assume that we have a point charge without energy loss, without electron captures and losses, etc.).

Recent experimental work is essentially dedicated to incident ion problems. It seems that recent theoretical and experimental works are very loosely bound. How do you see the future developments in both parts of the fundamentals of secondary emission?

Author: For proton energies above the stopping power maximum (about 100 keV) one may treat the proton as a bare nucleus, since the cross section for electron capture is small. As mentioned above, one may exploit results from electron-induced emission to proton-induced emission and vice versa in this velocity region. The energy loss of the primaries plays no significant role except for very insulating materials, in which $|dE_0/dx|$ in Eq. (2) is small. Then in the semiempirical description one may say that the primary particles suffer an appreciable energy loss over the characteristic escape depth of the secondaries.

A typical disadvantage of considering spectra or yields from primary electrons of energies much below 2 keV is that the electron range may be comparable to the characteristic escape depth. It means that it is no longer feasible to use the decoupling Eq. (1) of the yield into a simple expression that contains the surface value of the deposited energy.

Another substantial problem in interpreting the data from electron-incidence is that the stopping power for primary electrons below 10 keV is not very well known for heavy materials, cf. Sect. II in Schou (1988).

On the other hand, the proton stopping is known relatively well, and the spectra from metals do not indicate any influence of possible energy loss through the escape zone (Hasselkamp et al. (1987)). The protons are superior to primary electrons of the same velocity for these reasons.

A. Dubus: Some features like the electron emission from self-supporting thin films and the δ-η curves for thin films on substrates (incident electrons) are neglected in the recent work on electron emission. I think that much information can be taken from such features. What is your opinion about it?
Author: The backscattering of primary electrons is reduced from a thin film. It means that one may derive a relationship between the film thickness and the production of slow secondaries by the backscattered primaries (see Sect. II in Schou (1988)). The production of secondaries by transmitted primaries on the forward side of the film is much more complicated than on the backward side because the primary beam no longer is monoenergetic or monodirectional. For MeV protons one may neglect energy loss as well as angular scattering (see, e.g., Burkhard et al. (1987) and (1988)).