Measurement of the Energy Spectrum of Secondary Electrons Ejected from Solids by Positron Impact

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Energy distributions of fast secondary electrons ejected from Cu and Si bombarded by positrons of energies in the range 50 to 2000 eV, incident at glancing angles ($\leq 5°$) and at 35°, have been fit to the form AE^{-m} proposed by E. N. Sickafus. The absence of electron backscattering and the reduction of cascade effects common in electron-stimulated secondary electron spectra allow the direct determination of m for comparison with theory. The values obtained rise from 1.5 at 2000 eV to about 2.5 at 50 eV, and are all higher than those found for electrons incident at higher energies (0.5–1.5). No significant dependence of the value of m on target species or angle of incidence was observed. [S0031-9007(97)03544-8]

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The emission of secondary electrons from solids has long been of interest for many reasons. As well as being a fundamental aspect of electron-solid interactions, it is also of practical importance in devices such as electron multipliers and electron microscopes [1,2]. It is also of importance in the exploitation of electrons as a probe of materials—for example, knowledge of the background secondary-electron energy distribution is a prerequisite to accurate line shape analysis in electron-induced Auger electron spectroscopy (EAES) [3]. This Letter presents the results of first measurements of the energy spectrum of fast secondary electrons, uncontaminated by a background contribution from backscattered primary electrons.

An energetic primary electron may transfer energy to an electron in a solid. The two electrons then undergo elastic and inelastic scattering events, some of which may involve the release of further secondary electrons, and a cascade process occurs. The energy distribution of those secondary electrons which emerge from the surface of the solid into the vacuum is dominated by a broad peak extending from zero to several eV, with a tail extending to higher energies.

Backscattering occurs when the primary electron experiences a large-angle elastic scattering event, or multiple small-angle elastic events, and is reemitted—possibly after multiple inelastic scattering—into the vacuum with between 0% and 100% of its incident energy. Therefore the energy spectrum of electrons leaving a solid consists of significant contributions from both secondary and backscattered electrons.

Sickafus [4–6] measured the secondary electron energy distribution $N(E)$ in order to attempt to understand the spectral features associated with Auger transitions. He studied the energy region corresponding to the shortest inelastic mean free paths for electrons, i.e., $10 \leq E \leq 1000$ eV (above the low-energy cascade peak referred to earlier). We shall hereafter term this energy range the "Sickafus region." From plots of $\log_{10} N(E)$ vs $\log_{10} E$ he found linear sections obeying the simple relation

$$N(E) = AE^{-m}, \tag{1}$$

where A and m are constants for a particular material and primary energy E_p. The parameter m was found to be typically ~ 1; $\log_{10} N(E)$ has linear segments sometimes bounded by regions with Auger electron peaks (the Auger electrons being regarded here as secondary electrons of fixed initial energies). Further measurements of m by Matthew *et al.* [3] and Greenwood *et al.* [7], both for primary electron energies of about 20 keV, yielded values falling between 0.5 and 1.5. m showed a dependence on atomic number Z reflecting the number of valence electrons in the target atom. More recently Matthew *et al.* [8] performed Monte Carlo simulations, for a primary energy of 5 keV, yielding similar results. No dependence of m on primary particle energy has yet been established.

Experimental studies of $N(E)$ in the Sickafus region have been limited by the difficulties associated with distinguishing between true secondary and backscattered primary electrons, a problem which is exacerbated at low incident beam energies. This problem is absent, however, in the case of positron-stimulated secondary electron emission. It has been experimentally demonstrated that the low-energy secondary electron cascade spectra for both incident electrons and positrons are similar [9,10], but no measurements have been made to date in the Sickafus region. In a preliminary measurement the authors obtained a value of m close to 2 for a 2 keV positron beam incident at glancing angle ($\leq 5°$) on copper [11], in disagreement with previous experimental and theoretical results for electrons. The work presented in this Letter was motivated by the evident need for further measurements of m for different primary positron energies, target species, and incident angles.

The measurements were performed using the University of East Anglia (UEA) electrostatic beam system [12] shown schematically in Fig. 1. Positrons from a 200 MBq ^{22}Na source are moderated at an annealed tungsten mesh, guided, and focused electrostatically onto the target. An electrostatic reflector in the incident

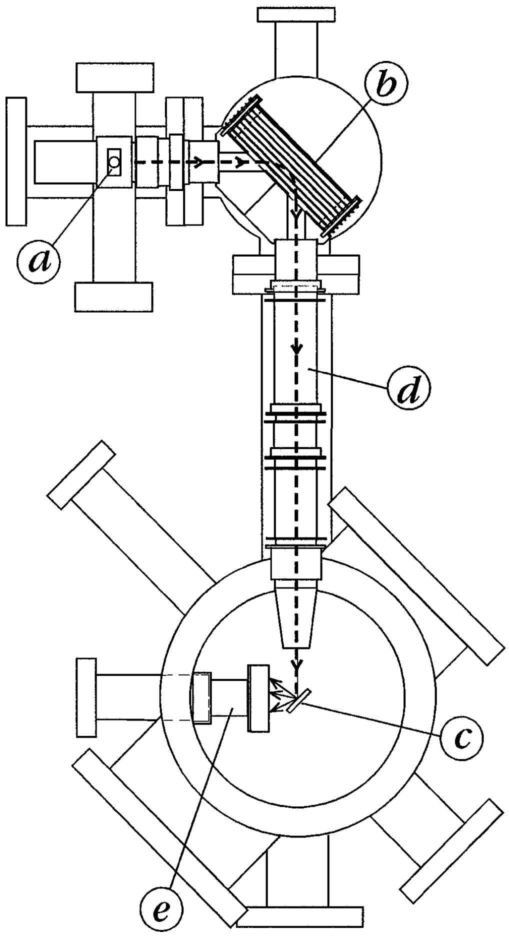

FIG. 1. Schematic of the UEA electrostatic beam system: (a) source, (b) electrostatic reflector, (c) sample, (d) electrostatic lenses, and (e) microchannel plate detector/RFA assembly.

beam arm essentially eliminates background counts due to high energy particles which could otherwise reach the target. By reversing the polarity of the potentials applied to the lenses an electron beam, generated by beta-positron-induced secondary electron emission from the moderator mesh, can be obtained. The system is evacuated to $\sim 10^{-8}$ Pa; sample cleaning is performed by repeated argon-ion sputtering and electron-beam heating, and surface contamination is monitored using conventional EAES.

Positrons or electrons leaving the sample surface which pass through a planar double-mesh retarding field analyzer (RFA) are detected by a channel electron multiplier array. A ramped voltage is applied to the RFA, and the transmitted particle count rate is recorded by a synchronously ramped PC-based multichannel scaler. A positive potential close to the incident positron beam energy is applied to a single mesh held in front of the RFA meshes, to prevent the production of secondary electrons from the meshes due to bombardment by backscattered positrons.

Integral energy spectra of secondary electrons emitted from copper and silicon were obtained for incident positron energies between 50 and 2 keV, and for glancing ($\sim 5°$) and 35° incident angles. The random, energy-independent background beneath the signal spectra was measured by cutting off the incident slow positrons by raising the potential V on one of the lenses in the incident beam arm such that eV was greater than the positron energy. After subtraction of this random background the data were differentiated; an example of the entire energy distribution thus obtained is shown in Fig. 2.

The spectra of energetic secondary electrons were plotted on a log-log scale, as illustrated in Fig. 3, to investigate if the distributions were of the form suggested by Sickafus [Eq. (1)]. Linear functions were found to be appropriate when fitting the higher energy regions of the spectra, allowing evaluation of the *m* values plotted in Fig. 4. Over similar energy ranges (expressed as a fraction of E_p), the values of m were found to be essentially independent of sample species or incident angle, but appear to fall as E_p increases.

The resolution of the system is limited by the planar nature of the RFA meshes in that a lower energy than the true value is attributed to an electron emitted from the sample at an angle other than normal to the plane of the analyzer. A detailed analysis of this effect, based on geometrical considerations, leads typically to an underestimation of m by about 4%. This is approximately compensated for by the corrections required to allow for the energy dependence of the efficiency of the detector (typically -6.5%). The net correction is within the uncertainty limits quoted for m.

The values of m lie outside the range of 0.5 to 1.5 for electron bombardment [3,7], although their energy

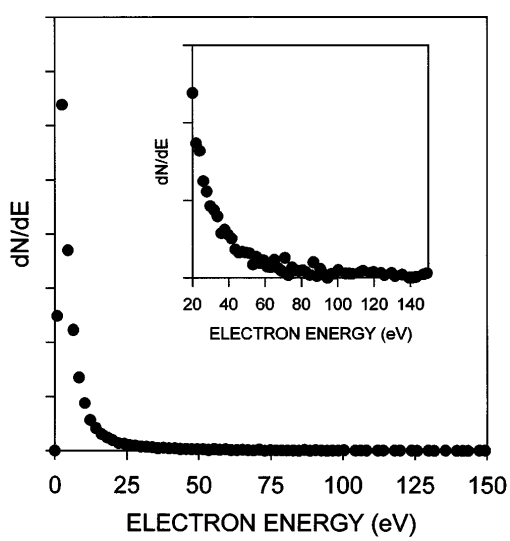

FIG. 2. Differential energy spectra of secondary electrons ejected by 300 eV positron impact on Cu. The main plot shows the low-energy electron peak; the inset shows the high-energy tail (the "Sickafus region") on an expanded scale.

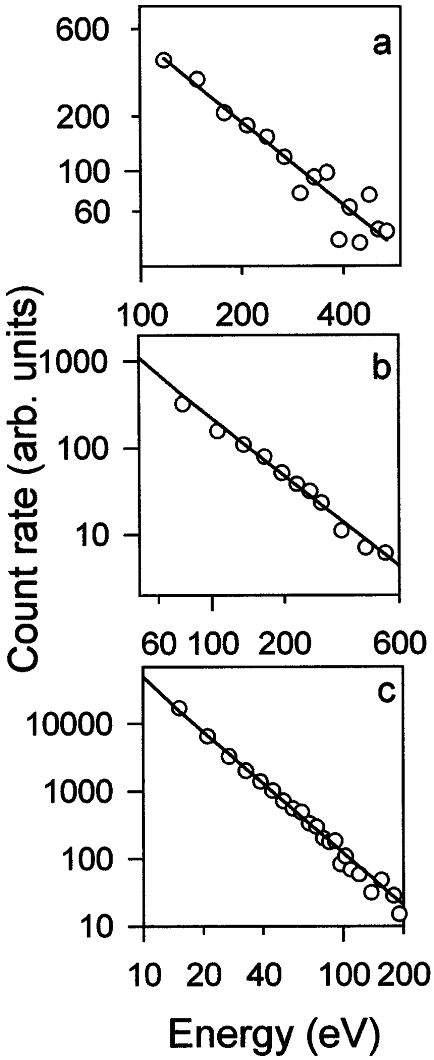

FIG. 3. Differential spectra of secondary electrons from Cu for an incident positron beam of (a) 2 keV, (b) 1 keV, and (c) 300 eV, shown on a logarithmic (base 10) scale. The straight lines are fits to the Sickafus regions.

dependence suggests that a high-energy asymptotic value close to the 1.1 reported by Greenwood *et al.* [7] for Cu at 20 keV might be approached. (This premise cannot be tested with the present system, for which the maximum incident projectile energy is 2 keV.)

To investigate the possible influence of the method adopted for the subtraction of the backscattered electron component in the electron beam measurements, the energy distribution of backscattered plus secondary electrons for 500 eV, 1 and 2 keV electron beams incident on Cu were measured. The results for 2 keV are shown in Fig. 5. A fit to these data in the energy region from 120 to 600 eV using the functional form suggested by Peacock and Durand [13], i.e.,

$$AE^{-m} + BE^{n}, \tag{2}$$

yielded a value of $m = 1.15 \pm 0.13$. The m values at 500 eV and 1 keV were 1.64 ± 0.26 and 1.22 ± 0.23, respectively. It is clear from Fig. 5 that the potential for systematic error in isolating the true secondary electron energy spectrum from the total spectrum is much greater in the case of electron bombardment.

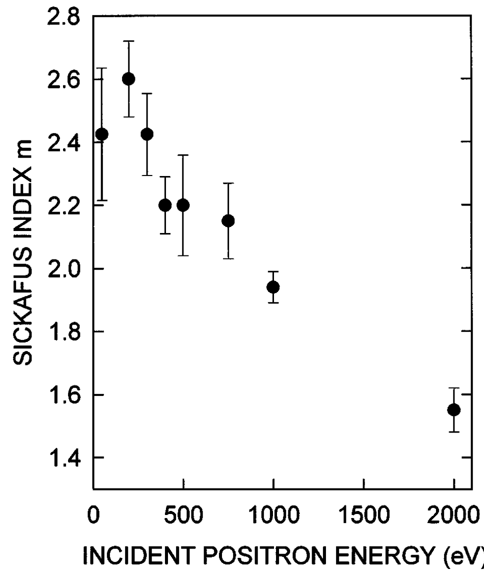

FIG. 4. Sickafus index m for secondary electrons ejected from Cu by positrons, as a function of incident positron energy.

The higher values of m in the present study using low-energy incident positrons probably result from the lower energy of the primary particle, the generation of secondary electrons at shallower depths beneath the surface, and the consequently lower probabilities for elastic and inelastic

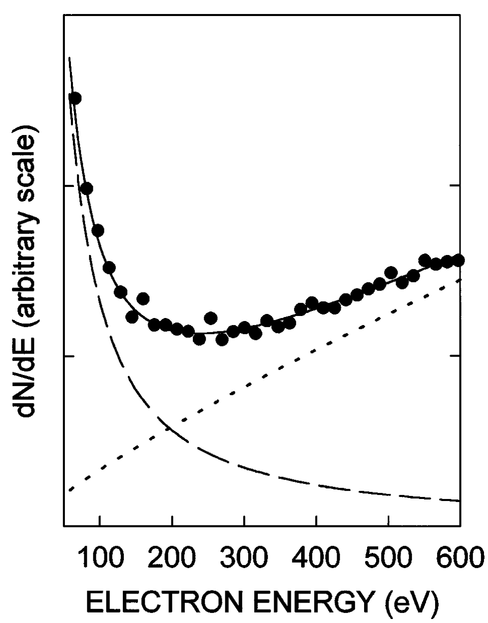

FIG. 5. Differential energy spectra of electrons leaving a Cu surface bombarded by 2 keV electrons (full circles). Solid line: fit to the form $AE^{-m} + BE^{n}$. Broken line: AE^{-m} (secondaries). Dotted line: BE^{n} (backscattered).

collisions before emerging into the vacuum. (There seems to be some evidence for a similar effect for incident electrons.) Matthew *et al.* [8] pointed out that the theory of Mott [14] suggests that, for incident particle energies much greater than those of the secondary electrons, the initial secondary electron spectrum—i.e., prior to any energy-loss collisions on the way to the exit surface—will have the form E^{-2}. The possibility of evaluating m for lower primary energies afforded by the use of positrons appears to have allowed the observation of an increase in the value of the parameter from the asymptotic limit ($\sim$1) for high incident particle energies—for which the depths of origin of the emerging secondary electrons is essentially constant—to a value closer to the Mott value of 2 at low incident energies.

Differences in the probabilities for inner shell ionization and Auger electron generation will also lead to some differences between the present m values for low-energy positron impact and those from earlier higher energy ($\sim$20 keV) incident electron beam measurements [3,7]. Ichimura *et al.* [15] postulated that broad features are introduced into the emitted electron spectrum $N(E)$ by the inner-shell ionization of target atoms by backscattered and secondary electrons, and Auger electrons create their own cascades of secondary electrons, modifying $N(E)$ and thus the value of m [4]. Preliminary results of the authors have indicated that, at the same high incident energy, electrons are more likely than positrons to be backscattered with high energies, consequently producing more energetic secondary electrons. Furthermore, at relatively low energies inner-shell ionization by positron impact is likely to be negligible compared with that characteristic of higher-energy electrons [16]; the probability of a low-energy Auger transition will thus also be smaller for an incident positron than an incident electron. One may conclude that by using low-energy incident positrons rather than high-energy incident electrons to generate secondary electrons, not only is the backscattered electron component eliminated, but segmentation effects arising from inner-shell electron ionization and associated Auger transitions are greatly reduced. The results of the present measurements are therefore potentially much more theoretically tractable than those from earlier electron experiments, providing a rigorous test of theory and simulation applied to electron spectroscopies.

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