

SECONDARY ELECTRON EMISSION FROM GLASS AND ITS PRACTICAL APPLICATIONS

Kazuo OOKA

Toshiba Research and Development Center, Tokyo Shibaura Electric Co., Ltd., Kawasaki, Japan

Bruce DUNN and John D. MACKENZIE

*Materials Department, School of Engineering and Applied Science, UCLA,
Los Angeles, California 90024, USA*

Received 13 October 1972

Secondary electron emission from glass and its applications are reviewed. The theoretical background together with experimental techniques of measurement are first discussed. The emission process from glass and its dependence on surface conditions, temperature and energy distribution are considered. Results on oxide and non-oxide glasses together with practical applications are then described.

1. Introduction

Electron emission from a solid is induced when the material is subjected to electron bombardment. This phenomenon, first observed by Austin and Starke in 1902 [1] has been utilized in the development of electron multiplier systems. These devices are used as detectors and amplifiers for ions, soft X-rays and photons as well as for electrons. Of all the solids whose secondary emitting properties have been exploited in such devices, glass is probably the most useful because of its ease of fabrication into convenient shapes, its chemical inertness, and the broad spectrum of properties it is capable of possessing. Despite its usefulness, the mechanism of secondary electron emission from glass is not well understood as evidenced by the fact that most devices are based on only one type of glass. This critical review is designed to generate more awareness of secondary electron emission from glass in the belief that glass will play an increasingly important role in electron multiplier systems.

1.1. Electron emission and the secondary yield curve [2–4]

As the incident or primary electrons strike the surface of the solid, a certain fraction of them are elastically reflected while the remainder penetrate the solid.

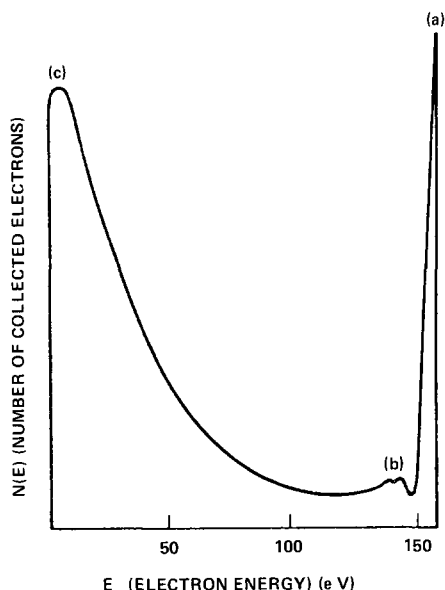


Fig. 1. Relative energy distribution of electrons emitted by silver after bombardment by primary electrons of 155 eV (after Rudberg [5]).

Of those penetrating, some may lose part of their energy inside the solid through inelastic collisions with lattice electrons thus returning to and escaping from the surface as a result of Rutherford scattering. Such electrons are inelastically reflected primaries. The bulk of the primary electrons that enter the solid will lose their energy by exciting lattice electrons into higher energy levels. These excited electrons ("true secondaries") move toward the surface and a certain fraction of them escape from the solid.

The term "secondary electrons" often includes all the electrons which escape from the surface and are collected by a positive collector. However, they should be differentiated as follows:

- (a) elastically reflected primary electrons
- (b) inelastically reflected primaries
- (c) true secondaries.

Fig. 1 illustrates the above mentioned categories as it considers the energy distribution of the electrons emitted by silver upon bombardment with primary electrons of 155 eV [5]. Peaks (a) and (b) corresponding to (a) and (b) above, are frequently termed "scattered" or "back scattered" electrons. The majority of emitted electrons, however, have relatively low energies. The maximum for this part of the curve, for most solids, exists in the vicinity of only a few electron volts. These slow electrons are "true secondaries".

The secondary yield, δ , is the ratio of emitted electrons per incident primary electron. In this definition all three categories of emitted electrons are included. One

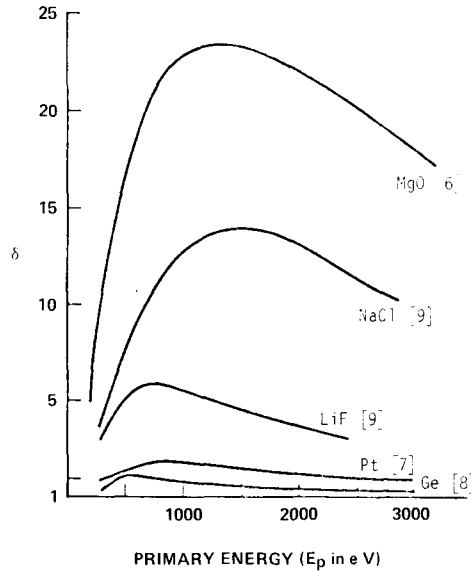


Fig. 2. Secondary yield versus primary energy for various materials [6–9].

of the most important relationships in secondary emission is that between the secondary yield, δ , and the primary electron energy, E_p . This constitutes the secondary yield curve. The examples shown in fig. 2 include insulators [6, 9], metals [7], and semiconductors [8].

Aside from quantitative differences, the curves for these materials exhibit the same general shape. At low energies, δ increases with energy, undergoing a maximum, δ_m , at some corresponding energy, $E_{p,m}$ and then subsequently decreasing. For metals, this decrease is far less prominent than with MgO or Ge. Table 1 gives typical values for many materials. In general, metals have maxima in the neighborhood of 1.0 to 1.5 while insulators possess a great range of values, stretching from 2 to 25. These materials are exceptionally sensitive to surface conditions as table 1 shows. The intrinsic semiconductors, Ge and Si, also have a δ_m of about unity and, according to Johnson and McKay, this value is independent of doping [8].

1.2. Fundamental theory of secondary emission

Dekker [2] has developed an elementary theory which explains the basic features of secondary electron emission. Essentially, the process is divided into two parts: the production of secondaries and their subsequent escape [10]. In a simplified representation the following general formula is offered, that

$$\delta = \int n(x) f(x) dx, \quad (1)$$

Table 1
Secondary yields for various materials [3, 17, 25]

Material	δ_{\max}	$E_{p, \max}$ (V)	E_I (V)	E_{II} (V)	Remarks
Ag	1.5	800	200	2000	
Ni	1.3	550	150	1500	
Na	0.82	300	—	—	
Pt	1.8	700	350	3000	
Si	1.1	250	125	500	Single crystal
GaAs	1.1	350	—	—	Single crystal
MgO	24	1500	—	—	Single crystal
MgO	18	1200	—	—	Thin film
NaBr	23	1600	—	—	Single crystal cleaved in vacuum
NaBr	16	1600	—	—	Before cleavage
KI	11	1500	—	—	Single crystal cleaved in vacuum
KI	3	500	—	—	Before cleavage
KI	5.5	—	—	—	Film

E_I and E_{II} represent the first and second "crossover potentials", those values of primary energy where the yield equals unity.

where $n(x) dx$ is the number of secondaries produced by one primary at a depth between x and $x + dx$, and $f(x)$ is the probability that a secondary produced at x reaches the surface and is emitted into vacuum. While the integral extends over the entire sample thickness, Dekker claims that only a 200 Å layer participates in the process [2].

The mechanism of secondary production involves a loss of energy suffered by primary electrons penetrating the solid due to the subsequent excitation of electrons to energies above the vacuum level of the material. Hence, when primary electrons strike a target there exists a function, $-(dE/dx)$ corresponding to the average energy lost by a primary electron per unit path length. As for the number of secondaries produced by a primary, this should be proportional to (dE_p/dx) , i.e.,

$$n(x) = -\frac{1}{\epsilon} \frac{dE_p}{dx}, \quad (2)$$

where ϵ represents the average energy required to produce a secondary. Thus, the nature of the (dE_p/dx) term describes how secondaries are produced in a solid. Using Whiddington's law,

$$-\frac{dE_p}{dx} = \frac{A}{E_p(x)}, \quad (3)$$

where A is a constant of the material, Dekker [2] derives an expression for $n(x)$ which implies that most of the secondaries are produced at the end of the primary path.

These features contradict the experimental results obtained by Young [11] on the transmission and energy dissipation of electrons in Al_2O_3 films. According to Young, the energy dissipation of the primary electron beam increases linearly with the fractional range covered. That is,

$$-\frac{dE_p}{dx} = \frac{E_p}{R}, \quad (4)$$

that the energy loss per unit path length is approximately constant throughout the primary electron range, R . This analysis predicts that a constant number of secondaries are created throughout the primary path, between $x = 0$ and $x = R$.

Aside from these two approaches, Kanter [12] has suggested an empirical method of finding $-(dE/dx)$ from the detailed measurement of electron scattering by thin foils. Using this method, Llacer and Garwin [13] were able to define a generation function which describes secondary production.

Once the secondary is created there is a certain probability that it moves towards the surface and escapes. Both Dekker [2] and Llacer and Garwin [13] believe that the probability of a secondary escaping from the solid is determined by an exponential absorption law. Dekker uses the form:

$$f(x) = f(0) \exp(-x/x_s), \quad (5)$$

where $f(0)$ is the probability for escape for a secondary produced at or very near the surface and x_s is the range of secondaries.

Using the equations just introduced, the following relationships may be shown. They are:

- (1) δ versus E_p exhibits a maximum at a certain primary energy,
- (2) the existence of a universal curve which should be valid for all materials.

The former relationship can be drawn by considering the δ versus E_p function at low and high primary energies [2]. The latter, first pointed out by Baroody [16] is obtained by plotting δ/δ_m versus $E_p/E_{p,m}$. The data points for a great number of materials are found to fall within a relatively narrow region.

1.3. Secondary emission process from materials

As shown in several articles [2, 4, 10, 14] secondary emission for metals stands on firm theoretical considerations. With insulators, however, adequate theoretical treatment is lacking because secondary production involves the excitation of electrons in the filled band and an accurate representation of the wave function for these valence band electrons has not yet been developed. Qualitatively, however, the

nature of secondary emission for both metals and insulators may be explained rather well.

Metals, generally, have low yield values, δ_m being in the neighborhood of 1.0 to 1.5. Yet they should be capable of producing many secondary electrons in that these are fairly large atoms with many loosely held outer electrons and relatively low ionization potentials. Electronically, their valence and conduction bands overlap and, thus, the creation of a "free" electron requires little energy. The reason δ is so low for metals must, then, be the result of a low escape probability. Due to band overlap, secondaries are able to interact with free electrons which results in a relatively high average energy loss suffered by the secondaries. Thus, metals are characterized by small escape depths of the order of 30 Å [15]. In this way $f(x)$ in eqs. (1) and (5) decreases very quickly for secondaries produced deep within the metal and causes a small yield value.

Insulators, commonly, are compounds whose bond strength and ionization potentials are very high. Electrons are very tightly bound, much more so than metals, and on this basis, one would expect a primary electron to create fewer secondaries in an insulator than it would in metal. That is, in this case it is much more difficult for a primary to create free carriers or secondaries than in metals because the band gap between the valence and conduction bands is rather sizeable.

The fact that the yield of insulators is much greater than metals must, then, be the result of a high escape probability. Unlike metals, secondaries in insulating materials do not interact with lattice electrons (a high energy loss mechanism) because good insulators typically have energy gaps greater than the energy of the secondary electron. Thus, excitation of electrons from the filled valence band is unlikely if not altogether forbidden. Instead, the escape process for secondaries in insulators is governed by interaction with lattice vibrations, a low energy loss mechanism. As a result, the effective escape depth for insulators with low surface barriers (electron affinity) may be as long as 200 Å [15]. In this way the low energy loss mechanism of phonon interaction leads to high escape probabilities for insulators and is responsible for the greater yields they exhibit.

2. Measurement of secondary electron emission

Measurements on insulators are more complex than those on conductive materials. The reason is that insulators are susceptible to surface charging because their electrons are so tightly bound. In the case of conductors, the surface is prevented from charging by the rapid movement of electrons in the conduction band. In measuring secondary emission from metals or conductive materials, the beam of primary electrons may be applied more or less continuously as there is no concern for surface charging. With insulators, however, a pulse method is often employed. This technique reduces the charge necessary for a measurement thereby reducing the surface potential. The time interval between pulses is utilized to restore the surface of the target

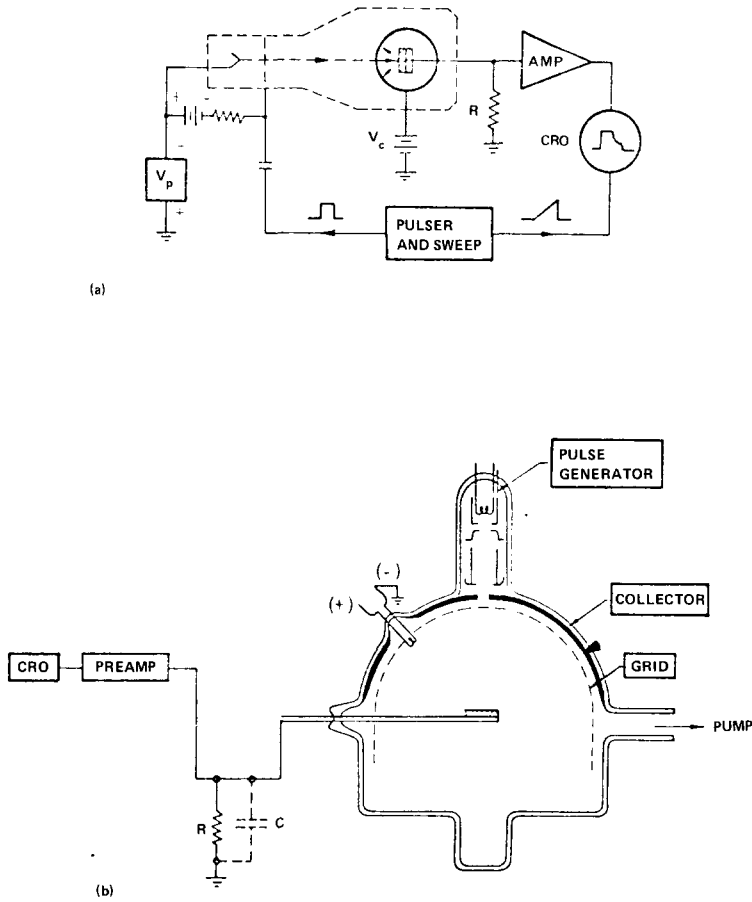


Fig. 3. Schematics of apparatus for secondary yield measurement with pulse method: (a) after K.G. McKay [19]; (b) after Whetten [17].

to a known potential either by heating it to produce sufficient conductivity or by flooding the surface with low energy electrons from an auxiliary filament. Whetten [17] has reviewed this technique and clearly shows the effects of surface charging [18].

Insulators will remain at the same potential only when the effective secondary yield is unity. The two primary energies where the yield is unity are called the first and second crossovers (E_I and E_{II}). When the yield is less than unity, the surface for insulators charges negatively. If the yield is greater than unity, that is, the primary energy is between the first and second crossovers, the surface charges positively with respect to the target.

The two most common methods of measurement are as follows:

(1) In this method primary and secondary currents are measured directly. During the entire measurement process, the collector is held positive to the target by +45 V. The collector current corresponds to the secondary current (i_s) while the combination of the target and collector circuits gives the primary current (i_p). Thus, according to the definition of yield as the ratio of secondary per incident primary:

$$\delta = i_s/i_p.$$

(2) In this method, all measurements are made in the target circuit. See fig. 3 [17, 19, 20]. When the collector is +45 V to the target, the current in the target circuit corresponds to the difference between the primary and secondary currents. Then, by changing the collector to be -45 V to the target, all the secondaries are returned to the target. In either method pulse or continuous currents may be used.

The two methods may not necessarily give identical results because of the effect of back-scattered electrons. In method I these high energy reflected primary electrons will contribute an additional current (i_n) at the collector so that

$$\delta = (i_s + i_n)/i_p.$$

Method 2 yields a different result because certain high energy back-scattered electrons will detract from the primary current and

$$\delta = i_s/(i_p - i_n).$$

If i_n is much less than i_s or i_p then both methods will reduce to the same value. However, this is not always the situation and the difference might be sizeable. Thus a knowledge of the magnitude of the backscattered fraction is necessary for a complete understanding of secondary emission from materials. In general, the back-scattered fraction seems to be in the neighborhood of 15% of δ for metals [21].

3. Secondary electron emission from glass

3.1. Secondary yield curves

Secondary yield curves for glasses were first obtained by Salow [22] using the pulse method. Blankenfeld [23] also measured the secondary yield for various glasses. Their results are illustrated in fig. 4 [35]. Mueller [24] measured the yield of Pyrex glass over the temperature range from 240 to 420°C, fig. 5. The variations among the curves are attributed to the changes in glass resistivity. Secondary yields for soda-lime and lead glasses are shown in fig. 6 [20].

The secondary emission properties of several glasses are summarized in table 2. Although the glass compositions have not always been given in the literature,

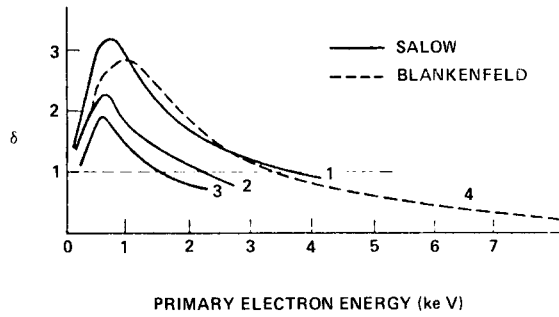


Fig. 4. Secondary yield curves of different glasses obtained by Salow [22] and Blankenfeld [23] (after Holland [35]). (1) "Grundlachglas", blown from molten glass ($5\ \mu\text{m}$). (2) Hard glass, blown from molten glass ($15\ \mu\text{m}$). (3) Cover-glass cleaned with HF and distilled water ($150\ \mu\text{m}$). (4) Unknown.

secondary emission from glass may be characterized as follows:

- (a) The maximum yield values range from 2 to 4.
- (b) The shape of the secondary yield curves resemble each other and those of insulators as well (fig. 2).
- (c) $E_{p,m}$ is in the neighborhood of 300–400 eV.
- (d) The first crossover occurs at energies as low as 20–30 eV.

As described in a previous section, the yield curves for insulators exhibit a different shape than those of metals because the disparity in their electronic structures results in different secondary emission mechanisms for these materials. On the other hand the secondary emission process for oxide glass should at least resemble that of insulators by virtue of their similarities in bonding, in electronic properties, and in the shape of their yield curves.

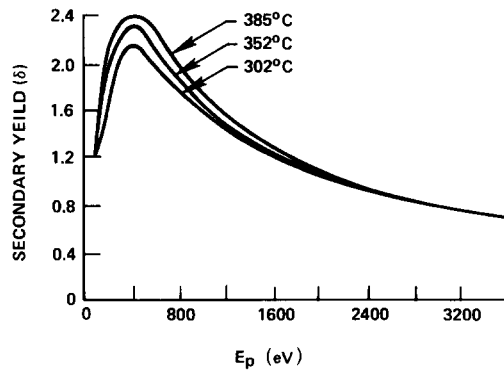


Fig. 5. Secondary yield of Pyrex glass as a function of primary electron energy (after Mueller [24]).

Table 2
Secondary emission properties of glasses

Glass	E_1 (V)	E_{\max} (V)	δ_{\max}	E_2 (V)	
Pyrex [24]	—	400	2.3	2500	
Lead [20]	25	350	2.9	>3000	
Soda-lime [20]	32	300	2.6	3000	
Silica [22]	30	400	2.1	2300	
Silicate [22]	<60	330	1.9	1700	Hf-acid and water cleaned
Cover-glass [22]	<50	440	2.9	3800	Heated to 1200° C in air
“Grundlach” glass [22]	—	440	3.1	4000	Blown from molten glass
	—	400	3.15	3500	Hf-acid and water cleaned
Hard glass [22]	<40	340	2.3	2300	Blown from molten glass
Glass* [23]	—	1000	2.8	3500	—
Iron-borate [52]	40	300	2.5	2500	—

* Glass composition not given.

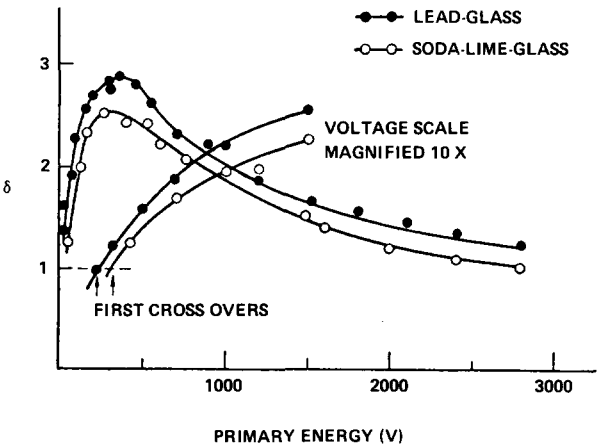


Fig. 6. Secondary yield curves of lead- and soda-lime glasses (after Dawson [20]).

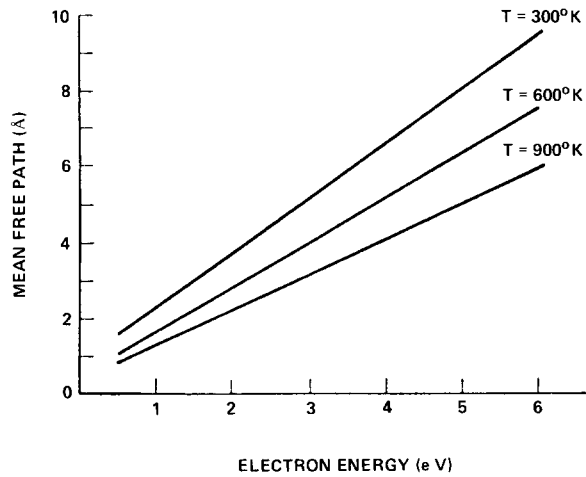


Fig. 7. Mean free path of internal secondaries as a function of electron energy for MgO (after Dekker [26]).

The δ_m values of glass are among the lowest observed for insulators. Alkali halides and alkali earth oxides (both as single crystals) exhibit maximum yields which are as much as ten times greater than those of glass while $E_{p,m}$ values are 3 to 5 times greater [9, 25]. The explanation of why such discrepancies exist between these two classes of insulators will provide insight into the secondary emission process from glass.

The primary difference between glass and crystal is the lack of long range order in the glass. The collision mean free path of an electron is determined by departures from periodicity in the solid. Thus, in single crystal MgO, the collision mean free path is several angstroms for an electron, fig. 7 [26], while in the disordered glass the mean free path should only be as long as the interatomic spacing, i.e., on the order of one to two angstroms [27–29].

The following example shows how the shorter mean free path of glass may lead to lower yields. Dekker [2] has calculated the mean depth of escape of secondary electrons at a primary energy of 1200 eV for MgO. This value is 180 Å. For a secondary electron of 5 eV, the mean free path (fig. 7) is about 7.5 Å. This means that a secondary produced at 180 Å will undergo 72 collisions before exiting from the surface. If it loses 0.05 eV per collision, the secondary will have lost 3.6 eV from the phonon interaction, and leave the material with 1.4 eV. This corresponds well with the data of Whetten and Laponsky (fig. 8) [30]. For a glass with a mean free path of 2 Å under the same conditions, a secondary at 180 Å will undergo 270 collisions. If it loses 0.05 eV per collision, the secondary will lose 13.5 eV. Since the secondary has only 5 eV initially, it will never be able to escape from the material at that depth. Thus we see that MgO will have secondaries escaping from the

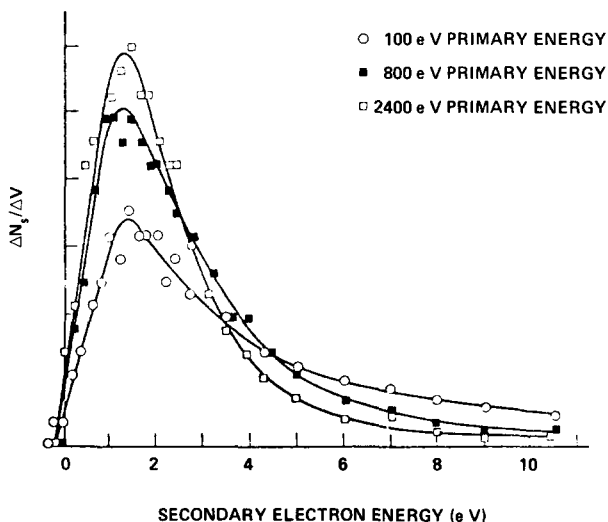


Fig. 8. Secondary electron energy distribution curves. The curves correspond to 100, 800 and 2400 eV primary energy and are normalized to include the same number of secondaries in each group (after Whetten et al. [18]).

material and contributing to the yield at depths where glasses will have no contribution.

3.2. Dependence on surface conditions

Experimental results show that the surface finish of a glass has profound effects on its secondary yield. Gentry et al. [31] roughened the surface of an electron tube by sand blasting. They found the secondary yield to be less than unity at primary energies greater than 100 eV. These are energies which for a smooth surface will have values exceeding one. Working at low primary energies, Fridrikhov and Shul'man [32] found the secondary yield of a glass to be slightly (5%) less when it was polished than when it had a roughened surface. In addition, the first crossover potential of the polished samples was 10 V greater than the unpolished one. The nature of these effects is not understood well at all. However, the dependence of electron affinity on surface conditions must be an important aspect.

Chuiko et al. [33] enhanced the secondary yield of lead silicate glass of high lead content by heat treatment in a reduced atmosphere. The surface resistivity dropped several orders due to the formation of a conductive film and the glass showed relatively high maximum yields of 3.5 to 4.3 at a primary energy of about 300 eV.

Research concerning the effect of surface conditions on the yield of crystalline insulators has also been performed. The most drastic influence of surface properties

is observed when alkali metal is vapor deposited on alkali halides [34]. NaCl had a δ_m of 6, but when Cs was vapor deposited on it δ_m increased to 22. This phenomenon is thought to be caused by the decrease in electron affinity of the surface. The process is widely exploited in commercial electron multipliers.

3.3. Temperature dependence

Glasses are essentially independent of temperature. Blankenfeld's results [23, 35] indicate that until 450°C, the yield remains constant for a given primary energy. Mueller [24] in measuring the yield of Pyrex glass over a temperature range of 240 to 420°C, found a variation slightly greater than that observed by Blankenfeld, but it was still relatively unchanged. He found δ to be 2.3 ± 0.1 at 400 eV primary energy.

One would expect the yield of glass to be independent of temperature on the basis of the mechanism previously presented. Due to the random structure of glass, the collision mean free path is already at a minimum and an increase in temperature could not possibly result in a decrease. This is contrary to crystalline insulators where a temperature increase results in a decrease in mean free path. Thus, a secondary undergoes more collisions per unit path length which causes greater energy dissipation by the secondary and a lower yield [26].

3.4. Angular dependence

Experiments have shown the secondary yield for polycrystalline materials to increase monotonically as the angle of incidence of primary electrons increases away from the normal [2, 4]. Since the depth of the secondaries produced in the solid for oblique incidence is less than that for perpendicular incidence at the same primary energy, a secondary has less of a distance to traverse in order to escape. Bruining [36] has interpreted these results on the basis of a simple cosine relationship.

Although studies on the angular dependence of the yield in glass have yet to appear, a behavior identical to that exhibited by polycrystalline material would be expected. The monotonic increase in yield has been observed only in polycrystalline solids because the multitude of randomly oriented grains serves to average secondary emission over all directions. Conversely, single crystals [37] show maxima (for the densely packed directions) and minima (at Bragg angles where primaries penetrate deeply) when the yield is plotted as a function of incident angle. The random structure of glass would insure that secondary emission be averaged over all directions and angles just as in the polycrystalline samples.

3.5. Energy distribution

The energy distribution of secondary electrons provides a means of determining the mechanism of secondary emission for different materials. Although the energy

distribution of secondary electrons from glass has not been reported, the results should be similar to those exhibited by good insulators because their secondary emission mechanisms parallel one another.

Shul'man and Dement'yev [38] (NaCl and KBr), Johnson and McKay [39] (MgO), Whetten and Laponsky [30] (MgO) have found that the most probable energy of emission is about 1 eV. Both Whetten and Laponsky and Shul'man and Dement'yev have observed that the secondary energy distribution depends on primary energy and that the relative number of low energy secondaries increases as the primary energy increases (fig. 8). Qualitatively, this effect may be described on the basis of the average path length of secondaries inside the crystal. When the primary energy is low, secondaries are formed close to the surface and, hence many escape without losing energy through interactions while in the crystal. At high primary energies, secondaries are created deeper within the material which means a greater distance must be traversed before escape may occur. Because of the greater distance, secondaries lose energy through interactions with lattice vibrations, and, consequently, their energy is attenuated. Thus, more low energy secondaries are to be found as primary energy increases, in agreement with the experimental data.

3.6. Miscellaneous effects

Outgassing and compositional change may be observed during electron bombardment of glass. Lineweaver [40] showed that high energy bombardment (10 to 27 keV) causes oxygen outgassing from assorted glasses.

The mechanism he proposed involved a compositional change in the glass, leaving a layer deficient in sodium and in non-bridging oxygen near the surface. Dawson [20] studied oxygen outgassing from lead and soda-lime glass by a pulse technique at energies of 100 to 1000 eV. The compositional change which occurs from high energy electron bombardment has been studied by Varshneya et al. [41], Borom et al. [42] and Hayami et al. [43] among others. This phenomenon is quite significant due to its obvious application in electron microprobe analysis. The formation of glass bubbles by intensive electron bombardment has also been observed [44]

4. Applications

One interesting application of secondary electron emission is related to band structure. Several researchers have used data from δ versus E_p curves to estimate the energy at the top of the valence band with respect to the vacuum level of materials. The assumption is that at the primary energy where the yield rises sharply, valence electrons absorb enough energy from one collision with a primary to cross the band gap and escape from the surface [45].

Another application is secondary electron emission spectroscopy [46], a non-destructive test which examines the energy distribution of the secondary electrons

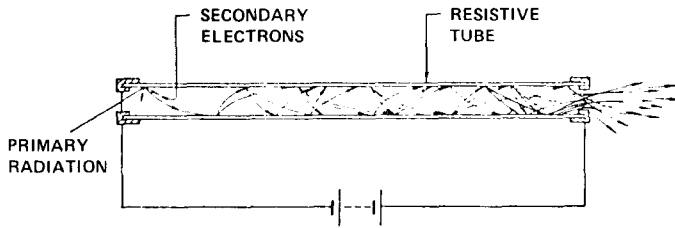


Fig. 9. Channel electron multiplier (tube dynodes) (after Manley [51]).

emitted by the material. When the primary energy is great enough to excite the atomic levels involved, electrons emitted by the Auger effect will comprise a part of the total secondary emission. Above this minimum energy, the primary energy level will not effect the Auger electron energy characteristics of the emitting atoms. These electrons contribute localized peaks to the secondary electron distribution. It is their characteristic energies which serves to identify the atoms producing them. Uncertainty in this method stems from surface conditions because without prior knowledge of the surface one cannot be absolutely sure of what is being measured.

The most common devices which exploit secondary electron emission are electron multiplier systems [47]. These devices are ideal detectors and amplifiers for electrons, ions, soft X-rays and photon radiation. They are capable of achieving a multiplication of 10^3 to 10^6 by virtue of a series of metallic electrodes, called dynodes, usually coated with a high yield material. The dynodes are arranged in successively increasing potentials so that the total number of electrons is multiplied each time the secondary electrons strike the emitting surface.

Recently, a new type of electron multiplier system has been developed. The channel electron multiplier utilizes glass as the secondary emitting material [48]. In the "field plate" type, both field and dynode plates are made from glass plates. A magnetic or electrostatic field helps to guide electrons down the channel. Multiplication of 1.3×10^7 has been obtained [49]. Another variety is the "parallel plate" dynode, where incident electrons are multiplied by successive collisions on both plates. Magnification in the range 10^7 to 10^8 has been reported [50]. The most sophisticated electron multiplier system developed thus far is the tube dynode channel electron multiplier [51]. As shown in fig. 9, a bundle of fine glass tubes is capable of a multiplication of 10^8 .

Normally in channel electron multiplier systems, glass plates or tubes are coated with high yield materials. Because stable, homogeneous films are difficult to obtain, there would be an advantage in using the glass surface itself as the secondary emitter. Recently, Kerr and Jorgensen [52] used an iron borate glass as the tube material and, without surface coating, obtained gains greater than 10^8 for single electron inputs.

Adams [53] has listed that the following requirement should be fulfilled by future glass dynodes.

- (a) The resistivity of the glass should be 10^9 to 10^{12} ohm · cm in order to give the potential gradient and to supply electrons to the surface.
- (b) For stable performance of the device, glasses with electronic conductivity are needed.
- (c) The yield should be greater than unity even at low primary energies of 40–50 eV.
- (d) X-ray absorbing glass is desirable for X-ray devices (image intensifiers, detectors, etc.). More detail concerning the application of glass as a secondary electron emitting material has been published in a previous paper [54].

5. Conclusion

The chemical stability and advantageous fabrication properties of glass should result in a wider appreciation of this material in devices based on secondary electron emission. To understand the secondary emission mechanism from glass more quantitatively and to develop more suitable glasses for these devices provides an intriguing challenge on both theoretical and practical levels.

Acknowledgements

We are grateful to Varian Associates, Palo Alto for partial support of this work.

References

- [1] L. Austin and H. Starke, *Ann. Physik* 9 (1902) 271.
- [2] A.J. Dekker, *Solid State Physics*, Vol. 6, eds. F. Seitz, D. Turnbull (Academic Press, New York, 1958).
- [3] D.J. Gibbons, in: *Handbook of Vacuum Physics*, Vol. 2, Part 3, ed. A.H. Beck (Pergamon Press, Oxford, 1966).
- [4] R. Kollath, in: *Handbuch der Physik*, Vol. 21 (Springer, Berlin, 1956) p. 232.
- [5] L. Rudberg, *Phys. Rev.* 50 (1936) 138.
- [6] N.R. Whetten and A.B. Laponsky, *J. Appl. Phys.* 28 (1957) 515.
- [7] R. Kollath, *Physik Z.* 38 (1937) 202.
- [8] J.B. Johnson and K.G. McKay, *Phys. Rev.* 93 (1954) 668.
- [9] N.R. Whetten, *J. Appl. Phys.* 35 (1964) 3279.
- [10] A.J. Dekker and A. van der Ziel, *Phys. Rev.* 86 (1952) 755.
- [11] J.R. Young, *Phys. Rev.* 103 (1956) 292; *J. Appl. Phys.* 28 (1957) 534.
- [12] H. Kanter, *Phys. Rev.* 12 (1961) 677.
- [13] J. Llacer and E.L. Garwin, *J. Appl. Phys.* 40 (1969) 2766.
- [14] O. Hachenberg and W. Brauer, *Advan. Electron. Electron Phys.* 11 (1959) 413.
- [15] R.E. Simon and B.F. Williams, *IEEE Trans. Nucl. Sci.* 15 (1968) 167.
- [16] E.M. Baroody, *Phys. Rev.* 78 (1950) 780.
- [17] N.R. Whetten, in: *Methods of Experimental Physics*, Vol. 4 (Academic Press, New York, 1964) p. 69.

- [18] N.R. Whetten, General Electric Res. Lab. Rept. No. 57-RL-1660, Nov. 1957.
- [19] K.G. McKay, J. Appl. Phys. 22 (1951) 89.
- [20] P.H. Dawson, Nuovo Cimento, Suppl. [I] 5 (1967) 612.
- [21] E.J. Sternglass, Phys. Rev. 95 (1954) 345.
- [22] H. Salow, Z. Techn. Phys. 21 (1940) 8.
- [23] G. Blankenfeld, Ann. Physik 22 (1951) 48.
- [24] C.W. Mueller, J. Appl. Phys. 16 (1945) 453.
- [25] M.V. Gomoyunova and N.A. Letunov, Soviet Phys.-Solid State 7 (1965) 316.
- [26] A.J. Dekker, Phys. Rev. 94 (1954) 1179.
- [27] A.I. Gubanov, Quantum Theory of Amorphous Conductors (Consultants Bureau, New York, 1965).
- [28] M.H. Cohen, J. Non-Crystalline Solids 2 (1970) 432.
- [29] N.F. Mott, J. Non-Crystalline Solids 1 (1968-69) 1.
- [30] N.R. Whetten and A.B. Laponsky, Phys. Rev. 107 (1957) 1521.
- [31] C.H.R. Gentry et al., British Patent No. 813904.
- [32] S.A. Fridrikhov and A.R. Shul'man, Soviet Phys.-Solid State 1 (1960) 1153.
- [33] G.A. Chiuko et al., Acad. Sci. USSR Bull. Phys. Ser. 28 (1966) 1415.
- [34] P. Pinard and M. Martineau, J. Phys. Radium 20 (1959) 561.
- [35] L. Holland, Properties of Glass Surfaces (Chapman and Hall, London, 1964) p. 497.
- [36] H. Bruining, Physics and Applications of Secondary Electron Emission (McGraw-Hill, New York, 1954).
- [37] A.B. Laponsky and N.R. Whetten, Phys. Rev. 120 (1960) 801.
- [38] A.R. Shul'man and B.P. Dement'yev, J. Tech. Phys. USSR 25 (1955) 2256.
- [39] J.B. Johnson and K.G. McKay, Phys. Rev. 91 (1953) 582.
- [40] J.L. Lineweaver, J. Appl. Phys. 34 (1961) 1786.
- [41] A.K. Vershneya, A.R. Cooper and M. Cable, J. Appl. Phys. 37 (1966) 2199.
- [42] M.P. Borom and R.E. Hannemann, J. Appl. Phys. 38 (1967) 2406.
- [43] R. Hayami and H. Wakabayashi, J. Ceram. Assoc. Japan 78 (1970) 138.
- [44] H.J. Dudek, Glastech. Ber. 41 (1968) 10.
- [45] A.B. Buckman and N.M. Bashara, Phys. Rev. Letters 17 (1966) 577.
- [46] L.A. Harris, General Electric Res. Rept. No. 68-C-201, July 1968.
- [47] J. Adams and B.W. Manley, Electr. Eng. 37 (1965) 180.
- [48] T. Imaoka, Mater. Electron. Japan 51 (1969).
- [49] G.W. Goodrich and W.C. Wiley, Rev. Sci. Instr. 32 (1961) 846.
- [50] H. Kanayama, in: 15th Proc. Applications Phys. Soc. Japan, (1968) 30-G-11.
- [51] B.W. Manley, A. Guest and R.T. Holmshaw, Advan. Electron. Electron Phys. 28A (1969) 471.
- [52] J.T. Kerr and L.L. Jorgensen, J. Non-Crystalline Solids 5 (1971) 306.
- [53] J. Adams, Advan. Electron. Electron Phys. 22A (1966) 139.
- [54] K. Ooka and J.D. MacKenzie, in: Proc. Ninth Intern. Congr. on Glass (1971) p. 793.