ELECTRON BEAM PROCESSING

During the 1930s, special steels, alloys, and ceramics were widely used in industrial products as mechanical engineering rapidly advanced. These materials are very hard and tough. Consequently, well-controlled cutting or processing of these materials at low cost became an important technical issue. To solve these problems, many new cutting tools, abrasives, and grinding wheels, as well as more effective machining processes and machine tools were developed. However, the most serious problem of tool wear in the machining process had not yet been solved.

In 1879 Sir William Crookes discovered that cathode rays can bombard and melt a platinum anode. Late in 1897 J. J. Thompson proved that these cathode rays are electron beams. In 1938 von Ardenne (1) employed magnetic-lens systems to focus beams for drilling small bores and indicated the possibility of using the energetic electron beam as a processing tool. That was the first electron beam processing in a defined manner, although Marcello von Pirani (2) proposed its industrial application and successfully carried out the first experiments on electron beam melting of refractory metals in 1905.

Electron beam processing is a technique that changes the shape or properties of a material or workpiece by using an electron beam, a directional flux of extremely small energetic particles. During electron beam processing, an electron beam machine produces a high-speed, energetic, electron beam and projects it onto the workpiece. A large portion of the high-speed electron beam penetrates through the surface of the workpiece. Then the kinetic energy carried by the beam is converted into thermal or chemical energy after interaction with the atoms of the workpiece. This thermal and chemical energy is directly involved in shaping and altering the material. Because electron beam processing is performed by injecting an electron beam into the workpiece and increasing the internal energy of atoms in the workpiece it is treated as a problem involving processing energy.

There are many unique features of using electron beams for material processing. One of them is that no solid machining tools are needed. Therefore, the tool wear problem no longer exists. Another unique feature of electron beam processing is that the electron beam can be focused onto a fine spot on the surface of the workpiece. The interaction between the electron beam and the material atoms occurs only in the area of the workpiece defined by the focused beam called the work point. The focused beam spot is deflected or scanned rapidly and accurately by a control signal. Its power density is very high and is easily varied by simply changing the acceleration voltage. In electron beam processing, the timing of energy feed, the work point, and the electron penetration range at the work point are easily controlled. Therefore, it is the most highly accurate, controllable process in material processing.

An electron beam machine has three essential parts: an electron gun, a vacuum system, and a control system. A diagram of electron beam processing equipment is shown in Fig. 1.

An electron gun is a device that generates, accelerates, focuses, and projects a beam of electrons onto a workpiece. First electrons are produced by cathodes or electron emitters. Then the electrons are accelerated by electrostatic fields to obtain higher kinetic energy and are shaped into an energetic beam. Finally, the guidance system, consisting of the electric and magnetic focusing lenses and deflecting system, transmits the beam to a work point on the workpiece.

The electron beam is properly generated and unrestrictedly propagated to the workpiece only in high vacuum. Depending on the material used for the electron gun and the application of the electron beam, the vacuum level requirement usually ranges from 10^{-3} mmHg to 10^{-8} mmHg. There-

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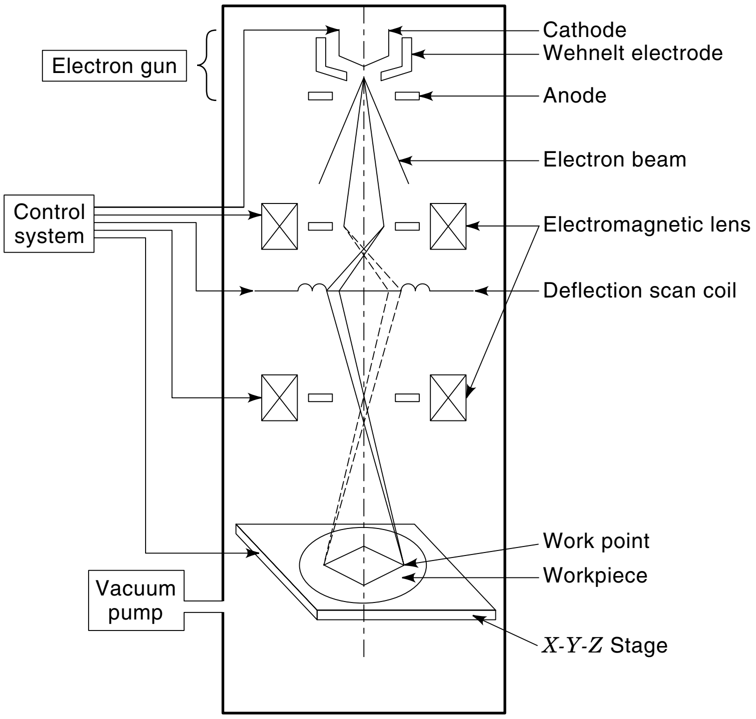

Figure 1. Electron beam processing equipment. Electrons are generated and accelerated by the electron gun, and guided through the column by the electromagnetic lenses and the deflection scan coil. Both the scanning system and the *X-Y-Z* stage are used to define the working point on the workpiece.

fore, the vacuum system, which creates a vacuum in the electron gun column and the working chamber, is one of the most important parts of the electron beam processing machine.

The control system provides the manipulative capability for electron beam generation, propagation, and timing. It also provides control over the workpiece translation and other functions.

Because electron beam processing works by varying the internal energy of atoms in the workpiece, its application has been extended well beyond cutting material. Other applications in machining include welding, drilling, melting, etc. It has also found its way into environmental control, chemical reactions, and semiconductor manufacturing. In the semiconductor manufacturing industry, the trend is toward smaller and smaller devices, *scaling down,* has continued since the formation of the industry in the early 1960s. Scaling down puts more pressure on the industry to find better methodologies with better controllability and stronger capabilities. The characteristics of electron beam processing, such as a fine focal point, high energy density, and ease of control, match some of the requirements well. Consequently, the application of electron beam processing in semiconductor manufacturing has grown explosively in recent years.

Two different categories of electron beam processing are widely utilized in semiconductor manufacturing. The first is thermal processing. This process makes direct use of the heat produced from electron beam energy. Electron beam annealing, deposition, and welding are classified in this category. The other category is reactive processing. In this process, ionization and excitation of constituent molecules of the material occur during the scattering of the incident electrons. Some excited molecules lose their energy by collision with other molecules and change into radicals. All of these ions, excited molecules, radicals, and secondary electrons are active species which induce chemical reactions inside the material. Electron beam lithography, polymerization, and depolymerization are all based on this process. This article is oriented mainly to the electron beam thermal processing, particularly to electron beam annealing and electron beam deposition. The second category is beyond the scope of this article. Refer to ELECTRON BEAM LITHOGRAPHY for details.

THEORY

A theory of electron beam processing is needed to design a machine and to provide a basis for analyzing electron–material interaction. This can be developed by understanding electron motion in electric and magnetic fields and energy conversion at the work point on the workpiece. Generally speaking, electron motion in electric and magnetic fields is described by Maxwell's equations. However, it is very difficult to solve the practical design problem of an electron beam system by simply applying boundary conditions to Maxwell's equations. Therefore, only the basic electron dynamics are given in this article. Similarly, only brief description of energy conversion and the thermal process at the work point is provided because of its complexity.

Basic Electron Dynamics

Assuming that the velocity of electrons during processing is very small compared to the speed of light, that the applied electric and magnetic fields are static or vary slowly so that they can be treated as constants, and that electrode shapes, potentials, and magnetic field configurations are known, the general equation of motion for an electron in electric and magnetic fields is written as:

$$\frac{d^2\boldsymbol{r}}{dt^2} = \frac{q}{m}(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \tag{1}$$

where q is the charge of the electron, m the mass of the electrons, and $\boldsymbol{r}$ is a position vector locating the electron with respect to any origin. $\boldsymbol{E}$ and $\boldsymbol{B}$ denote electric and magnetic fields, respectively. $\boldsymbol{v}$ is the velocity of the electron moving in the fields.

Electric Lens. Considering an axially symmetrical field system of the electron beam generating column, the electron beam passing through a common point near the axis can be made to pass through another common point by a relatively limited region of field variation. In analogy to light optics, it is appropriate to call the first common point the object, the second the image, and the region of the fields the electric lens. The properties and parameters of the electric lens are derived from the following paraxial ray equation:

$$\frac{d^2r}{dz^2} + \frac{dr}{dz}\left(\frac{V_0'}{2V_0}\right) + \frac{r}{4}\frac{V_0''}{V_0} = 0 \tag{2}$$

where V_0 is the potential on the axis. For example, because the derivatives V_0' and V_0'' are normalized with respect to V_0, it is understandable that the field distribution rather than the intensity of the potential determines the electron trajectories. The equation is unchanged in form even if a scale factor is applied to the location r. This indicates that all trajectories parallel to the axis have the same focus regardless of their initial radius. It should be noted that the electron charge q and electron mass m are absent from the ray equation. This implies that the equation is also applicable to other particles, such as ions. Using the ray diagram in Fig. 2, two focal lengths of a thin electric lens are obtained from Eq. (2) as

$$\frac{1}{f_i} = (-1)^i \frac{1}{4\sqrt{V_i}} \int_1^2 \frac{V_0''}{\sqrt{V_0}} dz \quad i = 1, 2 \tag{3}$$

where V_1 and V_2 are the potentials immediately before and after the electric lens region on the z axis, and the relationship between two focal lengths is similar to that in optics:

$$\frac{f_2}{f_1} = -\frac{\sqrt{V_2}}{\sqrt{V_1}} \tag{4}$$

where $\sqrt{V_i}$ is equivalent to the optical index of refraction N_i.

Magnetic Lens. As with electricity, an axially symmetric magnetic field also has lens characteristics and is called a magnetic lens. The paraxial ray equation for a magnetic lens is written as

$$\frac{d^2r}{dz^2} = \frac{\frac{q}{m} r B_0^2}{8V} \tag{5}$$

where B_0 is the magnetic field on the axis and V is the acceleration voltage. Clearly, the magnetic lens effect depends on the charge and mass of the electrons involved. The magnetic lens is symmetrical because the equation is unchanged if B_0 is reversed in sign. The spatial invariance of the magnetic lens ensures that electronic imaging is performed without distortion near the axis. Similar to the electric lens, the focal lengths are given as

$$\frac{1}{f_2} = -\frac{\frac{q}{m}}{8V} \int_1^2 B_0^2 \, dz \tag{6}$$

and

$$f_1 = -f_2 \tag{7}$$

The symmetry in Eq. (5) has been applied to obtain Eq. (7). Because electrons have a negative charge q, the back focal length f_2 is always positive. Therefore, a magnetic lens is always convex.

Bipole Element. Electron beam deflection is achieved by using electrostatic and magnetic bipole elements. An electrostatic field bends the passing electron beam toward the positive pole, and a magnetic field deflects the beam in the direction perpendicular to the direction of the field. A pure magnetic field changes the direction of an electron's motion but not its speed. The relationship between a magnetic field and the curvature of the electron path is given by

$$R = \frac{mv}{qB \sin\theta} \tag{8}$$

where R is the instantaneous center of curvature and θ is the angle between the magnetic field and the velocity vectors.

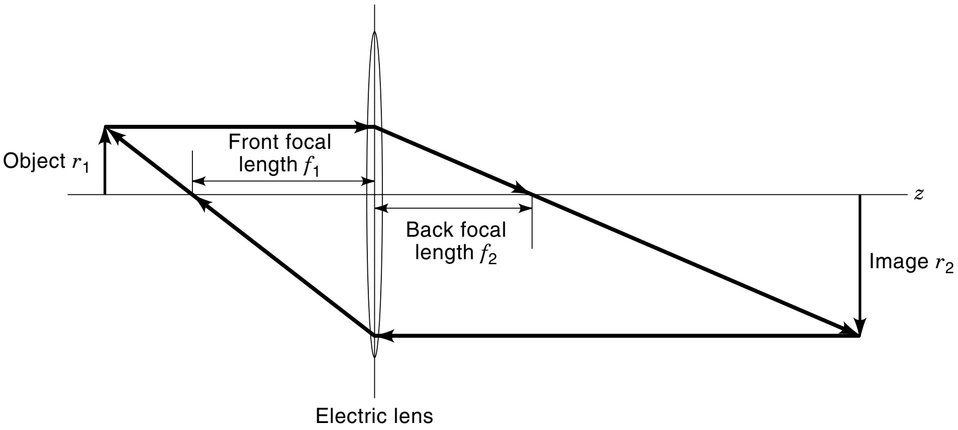

Figure 2. Ray diagram of electric lens. It is used for deriving the focal lengths of a thin lens.

Equations (1)–(8) describe the focusing, imaging, and deflection of an electron beam and provide the basic electron dynamics needed in designing a simple electron beam system.

Energy Conversion at the Work Point

Electron beam processing is a process that directly involves processing energy. It converts external electron kinetic energy into the internal energy of atoms at the work point on a solid workpiece. Then the surface treatment of the solid or the removal of the surface atoms is performed by the mechanism of consolidation or separation at the atomic scale. According to the theory of the thermodynamics of solids, an atom of a solid has an internal free energy U which is expressed as

$$U = G + H + E_e + E_k \tag{9}$$

where G, defined as Gibbs energy, is the potential energy for chemical or electrochemical decomposition or activation; H is the thermal energy due to atomic vibration around the lattice site; E_e is the internal elastic strain energy, an accumulation of the potential force over the displacement of the atom from its lattice site; and E_k is the linear kinetic energy.

The summation of the Gibbs energy G and the internal elastic strain energy at the atom lattice site E_{eo}, are given by

$$F = G + E_{eo} \tag{10}$$

which is defined as the minimum Helmholtz free energy that holds the atom at its lattice site.

To displace the atom from its lattice site or remove it from the surface of the workpiece, the internal free energy of the atom must be increased beyond the level of Helmholtz free energy at the surface of the workpiece. The free energy necessary to displace or remove the atom is obtained by increasing the amplitude of thermal vibration or the linear kinetic energy of the atom. This is done through collision with an impinging external electron in electron beam processing.

Inside an electron beam processing machine, an acceleration voltage V is applied to an electron gun so that an electron carrying a charge q is accelerated in the electrostatic field and obtains kinetic energy given by

$$E = qV \tag{11}$$

Usually the acceleration voltages used in electron beam processing are in the range of 10 kV to 150 kV. When acceleration voltages exceed 100 kV, relativistic effects must be taken into account. In such cases the kinetic energy absorbed by the electrons during their trajectory through the accelerating field is given by

$$\begin{aligned} E = qV &= m_0 c^2 \left[\frac{1}{\sqrt{1 - \left(\frac{v_e}{c}\right)^2}} - 1 \right] \\ &= \frac{m_0}{2} v_e^2 \left(1 + \frac{3}{4}\frac{v_e^2}{c^2} + \frac{5}{8}\frac{v_e^4}{c^4} + \cdots \right) \end{aligned} \tag{12}$$

where m_0 is the electron rest mass, v_e is the electron velocity, and c is the speed of light.

After the energetic electron beam passes through the electric and magnetic lenses and the additional beam shaping system, it is projected toward the workpiece. Once the beam reaches the workpiece, several different phenomena occur. As can be seen in Fig. 3, a certain portion of incident electrons are backscattered by the surface, and the so-called secondary processes excited by the incident electron beam produce X-ray, secondary-electron, and thermionic electron emission. About 99% of the electron beam penetrates through the surface layers and transfers its kinetic energy to electrons of the outer shells of the workpiece atoms. This effectively supplies the energy necessary to increase the internal free energy of the atoms, mostly in the form of heat. The heat generated results in a temperature rise in the workpiece, heat conduction from the zone of energy conversion to the surroundings, and heat radiation from the heated surface.

Upon the interaction with the surface of the workpiece, most of the electron beam energy is absorbed by the workpiece and converted to heat by a thermal process within a volume given by

$$\delta = \frac{d^2\pi}{4} D \tag{13}$$

where d is the focal spot diameter of the incoming electron beam on the workpiece and D is the penetration depth into the material. An empirical relationship among the penetration depth D, the electron acceleration voltage V, and the mass density ρ of the metal has been given by Whiddington (3):

$$D = 2.2 \times 10^{-11} \frac{V^2}{\rho} \tag{14}$$

Thermal Process

The thermal process caused by electron beam energy follows the basic equation of heat conduction theory, as do all beams caused by various energy forms, such as laser beams (4). Assuming that the thermal properties of the materials do not vary with working temperature and that no latent heat accompanies the thermal process, the basic boundary and initial equations in a semi-infinite solid are given in cylindrical coor-

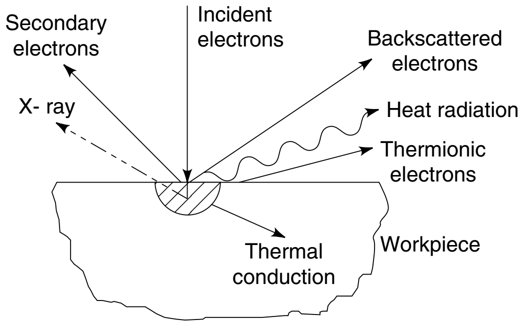

Figure 3. Energy conversion at the work point. Although different phenomena occur while the electron beam impinges the workpiece, about 99% of the electron beam will penetrate through the surface layers and transfer its kinetic energy to electrons of the outer shells of the workpiece atoms.

dinates by

$$\frac{\partial T}{\partial t} = \kappa \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right) \tag{15}$$

$$-\lambda \frac{\partial T}{\partial z} = q(r,t) \quad \text{at } z = 0 \tag{16}$$

$$T = 0 \quad \text{as } r, z \to \infty \tag{17}$$

$$T = 0 \quad \text{when } t = 0 \tag{18}$$

where κ is the thermal diffusivity, λ is the thermal conductivity, and $q(r,t)$ is the power density of the input electron beam. If $q(r,t)$ is independent of time and has a Gaussian distribution, that is,

$$q(r) = Q \exp[-(r/\sigma)^2]/\pi\sigma^2 \tag{19}$$

then the temperature rise T at the workpiece surface ($z = 0$) is expressed as

$$T = \frac{Q}{\pi^{3/2}\lambda\sigma} \int_{\tan^{-1}(1/2\sqrt{\beta})}^{\pi/2} \exp(-m^2 \sin^2 \varsigma)\, d\varsigma \tag{20}$$

where σ is the standard deviation radius, $\beta = \kappa t/\sigma^2$, and Q is the total input surface heat per unit time and $m = r/\sigma$. The temperature rise T along the z-axis is given by

$$T = \frac{Q}{\pi^{3/2}\lambda\sigma} \int_{\tan^{-1}(1/2\sqrt{\beta})}^{\pi/2} \exp(-m^2 \tan^2 \varsigma)\, d\varsigma \tag{21}$$

where $m = z/\sigma$.

This temperature rise varies the internal energy of the atoms and heats up the workpiece. The heat generated in the workpiece or the excitation and ionization of atoms and molecules is the basis of all electron beam processing techniques. The usually unwanted side effects include electron backscattering, the previously mentioned secondary processes, and heat conduction and radiation.

EQUIPMENT

The equipment for electron beam processing is basically the same as that for electron microscopy, only different in scale. It consists of three major parts: an electron gun, a vacuum system, and a control system, (see Fig. 1). The electron guns are the core characteristic of the electron beam processing technique. Therefore, this section is focused mainly on electron guns, including source generation, beam shaping, and the beam guiding system.

Based on the physical laws of electron emission and the desired energy conversion at the work point, almost all guns are of similar design, although they might differ widely in beam power, acceleration voltage, and electron current. In the gun, free electrons are first generated from emitters, or cathodes, and are then shaped into a well-defined beam, which is ultimately projected onto the work point. The common concerns of source generation and beam shaping systems are described here.

Source Generation

Emission. There are two kinds of electron emission. The first kind, called thermionic emission, happens when emissive materials are heated up to a high enough temperature. The second type is field emission, in which electrons are produced due to an intense applied electric field. Because thermionic emission has higher efficiency in producing electrons at lower cost, it is widely used in industry and is our primary concern here.

According to quantum dynamics, electrons are at rest in the ground state at 0 K and their energy levels and bands are well defined. As the temperature of the material increases, some electrons obtain more energy and jump to higher energy levels. When the temperature is high enough, the electrons obtain sufficient energy to overcome the natural barrier, the work function, that prevents them from escaping. In particular, as the temperature increases, the electrons near the upper limit on the conduction band of metals smears and stretches out. Some of the conduction electrons obtain enough energy to overcome the potential barrier at the surface of the metal. Then these electrons may be drawn off by applying a suitable field. If the field is sufficiently high to draw all the available electrons from a cathode of work function Φ, the saturation current density J obtained at temperature T is given by the well-known Richardson–Dushman law

$$J = AT^2 \exp\left(-\frac{q\Phi}{kT}\right) \tag{22}$$

where A is a constant determined by the material and k is Boltzmann's constant.

In practical electron gun design, less than the saturation current is usually drawn from the gun because the field is not strong enough to draw off all available free electrons from the cathode. Therefore, the residual electrons are accumulated near the surface of the cathode and form an electron cloud layer. This operation, termed space-charge-limited, has the advantage that a smaller virtual cathode that has a stable charge density, essentially independent of cathode temperature, is formed slightly in front of the cathode. The current that flows between parallel electrodes is given by Child's law (5):

$$J = \frac{4\sqrt{2}\epsilon_0}{9}\sqrt{e/m}\frac{V^{3/2}}{L^2} = 0.0233\frac{V^{3/2}}{L^2} \tag{23}$$

where V is the acceleration voltage and L is the distance between the cathode and anode.

The current density in the range of space-charge-limited emission and temperature-dependent emission is shown in Fig. 4. Most cathodes in electron guns operate in the transitional range between the space-charge and saturation regimes so that the desired emission current density is obtained at the lowest cathode temperature.

Equations (22) and (23) give the conditions for obtaining the required emission from a given cathode material. As long as the material is specified, the preliminary cathode design can be completed.

Materials. Free electrons are obtained from the cathodes made of many kinds of materials. The primary gun design requires, however, that the cathode has a low work function

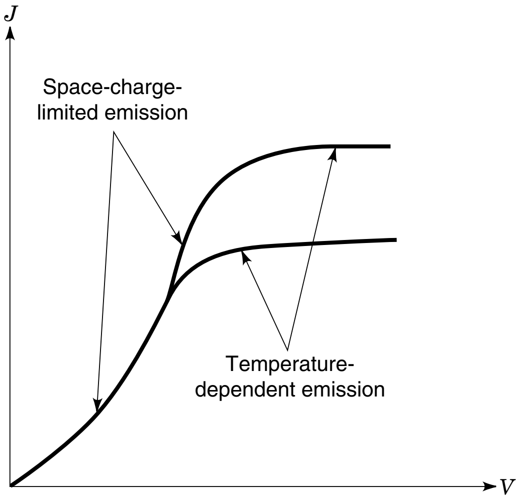

Figure 4. Space-charge-limited emission and temperature-dependent emission. Most cathodes in electron guns operate in the transition range between the space-charge and saturation regimes so that the desired emission current density can be obtained at the lowest cathode temperature.

and good thermal efficiency, supplies an adequate emission current, and is simple to construct. Among all of the constraints, the vacuum condition of the electron gun puts strong limits on the choice of cathode materials.

At low vacuum levels (less than 1×10^{-5} mmHg), materials with low work functions and high bulk evaporation rates, such as barium, are frequently used. The material is contained within the body of another material which provides structure and shape for the cathode, and then migrates to the surface by diffusion. This kind of cathode is called a dispenser cathode. The dispenser cathode generates and maintains an excess of barium metal at its surface and relies on that excess for its emission properties. In this configuration, the evaporation of the materials can be slowed down and easily controlled.

At vacuum levels higher than 1×10^{-5} mmHg, the choice of cathode material is restricted to refractory metals, which have higher work functions and operate at higher temperatures. The most attractive refractory metals are tungsten and tantalum whose work functions are 4.55 and 4.1 electron volts, respectively. The melting point of tungsten is 3410°C, and that of tantalum is 2996°C. At temperatures below 2500°C, tantalum emits 10 times the current of tungsten. Tantalum is also easy to work with and can be formed into a sheet to produce special cathode shapes.

If the vacuum is to be recycled to atmosphere but not operated above 5×10^{-6} mmHg, a cathode of lanthanum hexaboride (LaB_6), whose work function is 2.4 electron volts, is used (6). This arises from the need for relatively high emission current densities at lower emission temperatures. Among other activated cathodes, LaB_6 is much less sensitive to problems such as cathode contamination and lifetime, but its long-term stability and thermal cycling stability are still unsolved problems.

Among all of these cathode materials, tungsten is not the best in most respects, but for normal applications it is a cheap, robust, and reliable emissive source. As of today, tungsten remains the most important cathode material in the field of electron beam processing, even though tantalum, LaB_6, and tungsten with emission-increasing alloying elements are also widely used.

Beam Shaping and Guidance

After the free electrons are emitted from the cathode, they are shaped into a well-defined beam with the desired beam diameter and focal length and then guided to the work point on the workpiece. This is achieved through different gun design and via focusing and deflection by using the principles of electron optics.

Gun Type. A basic electron gun consists of a cathode, a focusing electrode, and an anode. It is called a two-electrode gun if the focusing electrode has the same potential as that of the cathode. A design with different potentials for the cathode and the focusing electrode is called a three-electrode gun. Multielectrode guns have several focusing electrodes or control electrodes at different potentials.

Analogous to the terminology in light optics, an electron gun is called an axial gun if the elements of the beam-generating system, the electrostatic field, and the beam itself are rotationally symmetrical. Three basic axial gun types are generally used: the telefocus gun, the gradient gun, and the Pierce gun.

The telefocus gun is a three-electrode gun (see Fig. 5) primarily designed to produce a relatively long focal length. The long focus effect is due to the hollow shape and negative bias of the Wehnelt electrode, which acts as a simple electrostatic lens. It operates as follows. First, the electrons near the cathode are pushed outward along the diverging electric field. Due to the special design, then the equipotentials between the Wehnelt electrode and the anode become flat and finally converge toward the anode (shown as dotted lines). At this final step, the electron beam obtains a net radial velocity inward. The magnitude of the net radial inward velocity is smaller than the initial outward velocity because now the electrons have higher energy. Consequently the electron beam converges quite slowly and has a long focal length. If the bias on the Wehnelt electrode increases, the field curvature in the cathode region also increases. Therefore, the focal length is longer because the starting electron beam diverges more. The ray traces are shown in solid lines. Position P is the focal point.

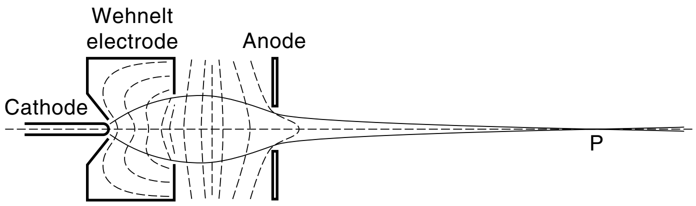

Figure 5. Three-electrode telefocus gun. Its long focal length is primarily due to the hollow shape and negative bias of the Wehnelt electrode, which acts as a simple electrostatic lens.

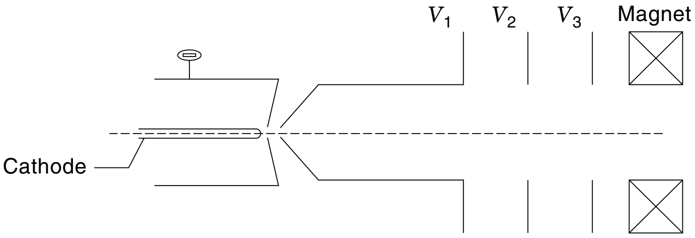

Figure 6. Triode gradient gun. Similar to the conventional triode, the relatively high voltages and large currents are controlled by a small "grid" voltage, V_1. Thus the total beam power may be varied over a wide range with a small variation in spot size.

The gradient gun (7) shown in Fig. 6 is a postacceleration gun. Similar to the conventional triode, the relatively high voltages and large currents are controlled by a small "grid" voltage V_1. Thus the total beam power may be varied over a wide range with a small variation in spot size. To take full advantage of the gun's capabilities, the total accelerating voltage must be much larger than the controlling voltage V_1. V_1 must also be high enough to draw adequate emission from the cathode.

In many applications in semiconductor manufacturing, uniform, high-intensity electron beams are required. It was suggested by Pierce that such a uniform electron beam could be obtained over a limited region if the region is considered a segment of extensive beam flow and the electrodes, including cathode and anode, are shaped to maintain the same voltage along the edge of the segment. Under space-charge-limited emission, the so-called Pierce gun is designed to produce a parallel or slightly divergent beam (see Fig. 7). In this design, a broad electron beam is emitted by a flat cathode and propagates as a parallel laminar flow with a sharp planar or cylindrical surface. To keep this beam propagating as a parallel beam, the shape of the electrodes outside the beam must be carefully considered. The simplest solution is to have a 67.5° angle at the cathode and the curved anode surface, which coincides with an equipotential. A spherically curved cathode converges the beam. However, the resultant focus point is relatively large because of the outwardly directed force of the space charge. The Pierce gun is a two-electrode gun and is easy to design. The beam can be parallel, divergent, or convergent. The efficiency of the gun can be as high as 99.9% or more.

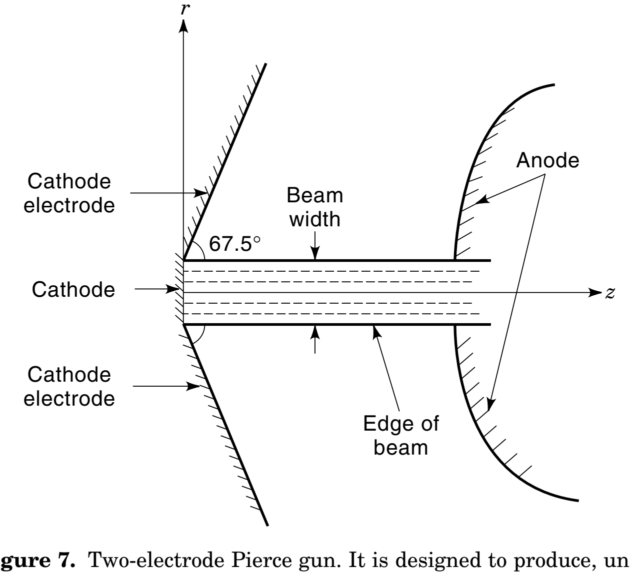

Figure 7. Two-electrode Pierce gun. It is designed to produce, under the space-charge-limited emission, a parallel or slightly divergent uniform high-intensity electron beam.

Beam Guidance. The beam shaped in the gun is characterized by the parameters of the focal spot. The most important focal spot parameters are the diameter and location of the focal spot on the axis, the current density and current density distribution on the focal plane, and the aperture. The object of the beam guidance system is to transform these parameters into parameters required by the particular application process on the workpiece. A simple beam guiding system is shown in Fig. 8. In this system, a focal point at the object plane is first deflected by a double-deflection system and then imaged and refocused onto the image plane. For some applications, the beam diameter formed inside the gun must be imaged either on an enlarged or reduced scale to obtain a beam with a defined diameter, a particular current density, and a specified power density on the workpiece. The beam current at the working point may be lower than the beam current in the gun through aperture limiting. Other applications may require that the beam is guided into the working chamber without any noticeable loss in beam current.

Like all other electron beam applications, beam guidance for electron beam processing is achieved via imaging, focusing, and deflection under the principles of electron optics. In general, rotationally symmetrical magnetic fields produced by magnetic-lens systems are used for imaging and focusing. Either plain or crossed magnetic bipole elements are often used for beam deflection. To turn the beam over wide angles, magnetic sector fields may be added for additional deflection.

Magnetic lenses are generated by permanent magnets and also by electrical coils. The simplest magnetic lenses are ironclad coils, as shown in Fig. 9. In this configuration, the magnetic induction is proportional to the excitation NI, where N is the number of turns and I is the coil current. The magnetic field profile and the electron optical features of the lens are totally dependent on the gap width w and the bore diameter D of the pole pieces. In practice, the aberration and astigmatism should also be considered in lens design.

It can be seen from Eqs. (6) and (7) that all magnetic lenses are convex lenses. These lenses are used either for producing a magnified image of the object or focusing a parallel electron beam to a fine point. Assuming that the front and back focal lengths of the convex "thin" lens are same, Newton's lens equation can be applied for electron beam formation:

$$\frac{1}{\xi} + \frac{1}{\zeta} = \frac{1}{f} \qquad (24)$$

where ξ is the distance between the object and the lens, ζ the distance from the lens to the image, and f the focal length of the lens. To obtain a real magnified image, both ξ and ζ should be greater than f. The magnification is defined as:

$$M = \frac{\zeta}{\xi} \qquad (25)$$

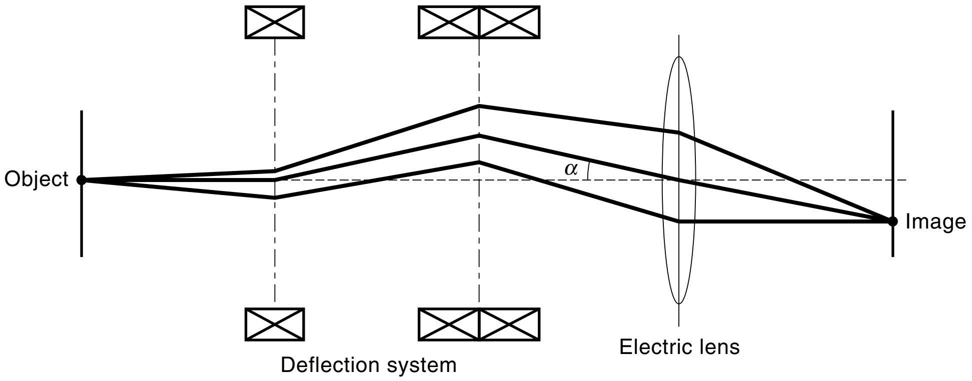

Figure 8. A double-deflection system in which a focal point at the object plane is deflected by α degrees at the image plane.

As in a well-designed optical imaging system, it is often necessary to change the magnification while operating the electron beam system. The magnification of the electron beam system is varied by changing the strength of its electric or magnetic lens. This is totally different from the light beam system, in which the magnification is changed by moving the optical lens or the objective back and forth.

Both electrostatic and magnetic bipole elements are used for beam turning and deflection. They are created by electrical fields between two plates or by magnetic fields between the opposite poles of a permanent magnet and inside current-carrying coils. In electron beam processing, the electrostatic bipole element is usually employed for beam blanking or some other special purposes.

There are many designs of magnetic bipole elements. In the simplest case, the field between the poles of a permanent magnet is used for deflection. The pole-piece spacing w and their widths b are usually much larger than the electron beam diameter. In most cases, magnetic fields for deflection elements are produced electromagnetically. The magnetic induction B is directly proportional to the excitation NI and indirectly proportional to the pole-piece spacing w. To obtain the highest possible induction at a given excitation, the magnetic circuit must have very large dimensions.

Narrow and wide angle deflection in a uniform magnetic field normal to the electron beam direction are shown in Fig. 10. Based on electron dynamics, the radius of the electron trajectory is given by

$$R = \left(\frac{2m}{q}\right)^{1/2} \frac{V^{1/2}}{B} = 3.37 \times 10^{-6} \frac{V^{1/2}}{B} \tag{26}$$

When the electron beam enters a limited magnetic field vertically (8), the beam deflection over a narrow angle is expressed by:

$$\sin\theta = 2.97 \times 10^{5} \frac{LB}{V^{1/2}} \tag{27}$$

where L is the field length. In a magnetic sector field, the deflection angle is found from the following equation:

$$\theta = \alpha - \beta_1 + \beta_2 \tag{28}$$

Clearly, the deflection angle is enlarged by increasing the sector angle α.

APPLICATIONS

Among the many applications described in the literature, one of the most important is the use of electron beams as energy carriers for locally heating workpieces in a vacuum. Electron

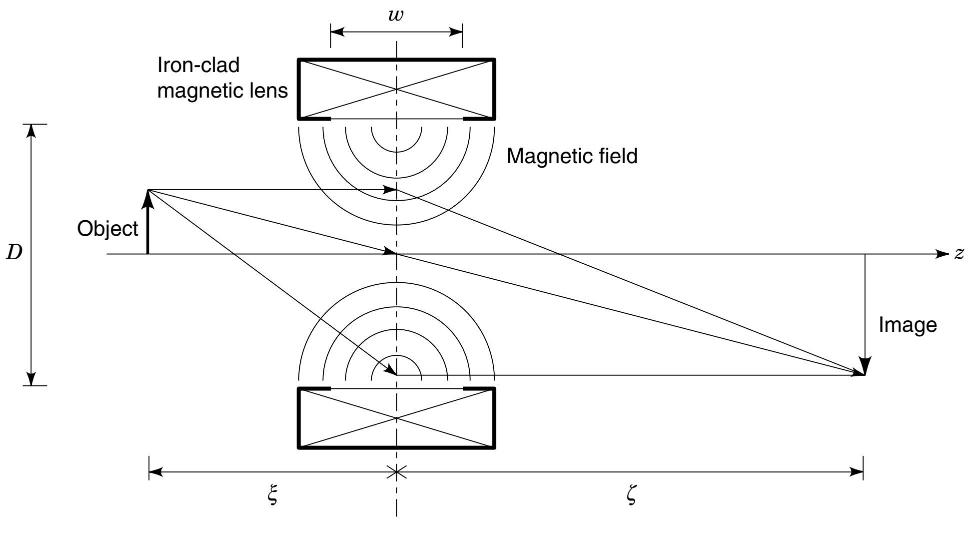

Figure 9. A magnetic lens generated by iron-clad coils, which is a basic element of the electron beam processing equipment to project an electron beam pattern to the workpiece.

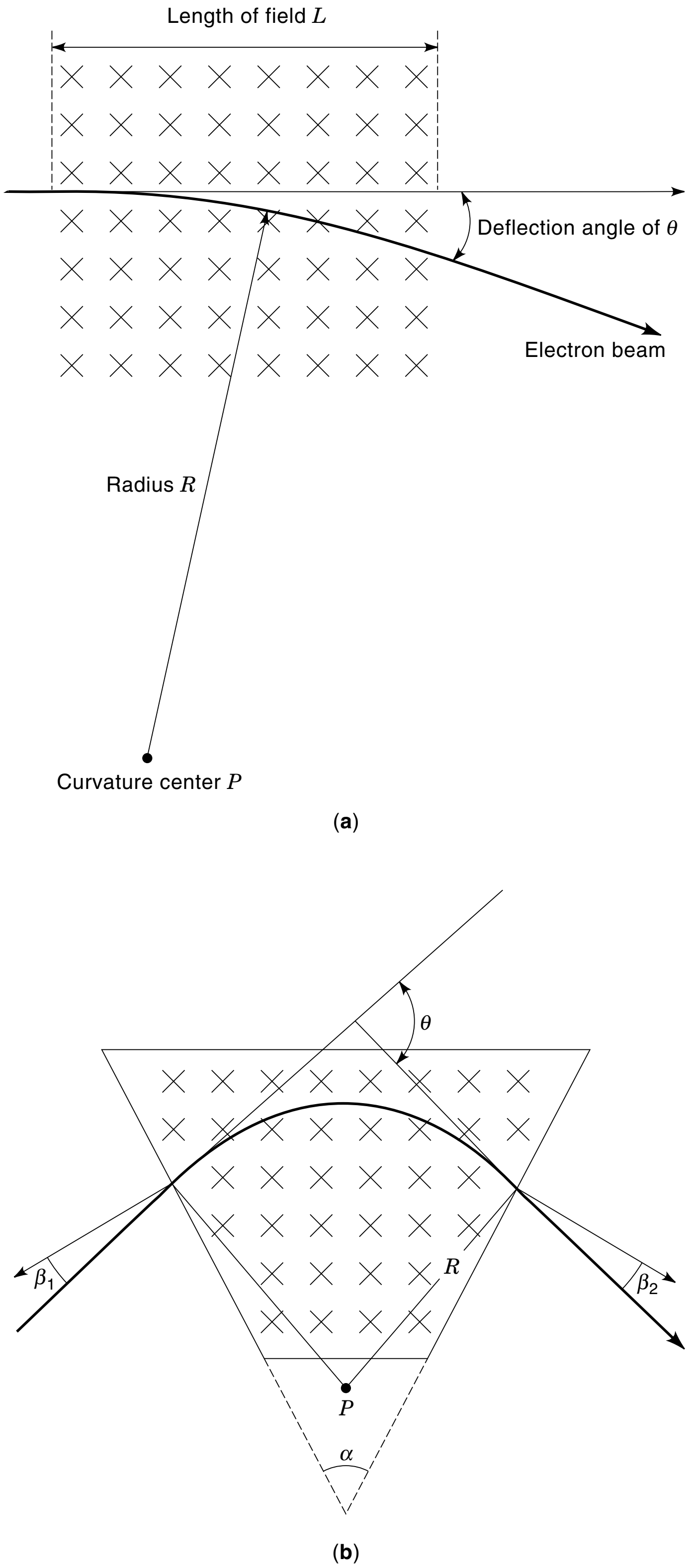

Figure 10. Electron beam deflection in a homogeneous magnetic field. (a) Deflection in a limited field; (b) bending in a sector field. The sector field produces a larger deflection angle.

beams are specially used to carry high power densities and to generate a steep temperature rise on the workpiece. Furthermore, the energy input at the work point can be accurately controlled with respect to time and space. With these characteristics, electron beam processing emerged as an alternative method for heat treatment in vacuums. It has been widely used in semiconductor manufacturing in the past three decades.

Electron Beam Annealing

Energetic ion beams (in the range of 10 keV to 200 keV) are used extensively to introduce dopants into substrates in manufacturing semiconductor devices. An energetic ion beam has several advantages over the conventional diffusion method: better dopant confinement, better dosage control, and very high dose reproducibility. It is also a low temperature process that reduces the total thermal budget of device fabrication. During ion implantation, ions penetrate into substrates and transfer energy to the crystal lattice through collision. Consequently, the local crystalline structure is destroyed and an amorphous layer is formed. To restore the crystalline structure, annealing is usually performed after ion implantation. Electron beam annealing (9) has proved superior to conventional techniques, such as annealing by furnace or laser beam, because of its many advantages: it is possible to control the annealed depth by electron energy; it is easy to control the positioning and motion of the electron beam accurately; and energy absorption is independent of the surface condition.

During electron beam annealing, an electron beam of constant power density is projected directly onto the ion implanted substrate surface to transfer energy. Depending on the energy profile of the electron beam, annealing is classified into two categories: pulsed electron beam annealing and scanning electron beam annealing.

Pulsed Electron Beam Annealing. As is clear from its name, this kind of annealing uses a pulsed electron beam. A single pulse of up to 100 ns and 30 keV is focused into a diameter equal to or greater than the semiconductor wafer. When transferred to the surface of the wafer, this amount of energy fuses the wafer surface up to 1 μm in depth. Therefore the molten layer goes well beyond the implantation depth and penetrates the unimpaired monocrystalline material. Because of heat conduction, the molten layer cools down rapidly, and the material grows epitaxially onto the crystal located underneath at an orientation given by the monocrystals. The recrystallization front propagates at a velocity of about 1 meter per second toward the surface, so that recrystallization is completed about 100 ns after the action of the beam pulse has ceased.

The mechanism of pulsed electron beam annealing is considered to be liquid-phase epitaxial regrowth due to melting. The resultant impurity redistribution profile after annealing is much flatter and deeper compared to that immediately after implantation and that in furnace-annealed wafers.

Pulsed electron beam annealing is a transient, rapid annealing process. It is considered an excellent method for thermally annealing GaAs to prevent escape of As and precipitation of Ga during the process.

Scanning Electron Beam Annealing. In scanning electron beam annealing (SEM), restoration of the crystalline structure takes place at a temperature just below the melting point of the semiconductor material. This can be carried out using an SEM machine or a welding machine equipped with a scanning apparatus.

To obtain well-defined temperature conditions and a rather low thermal load for the monocrystalline silicon, the semiconductor wafers must usually be in contact with a cooled copper plate, fixed by heat conducting adhesives. Electron energies of 30 keV and spot diameters in the range of about 10 μm to 100 μm are used. The necessary temperature holding time (0.1 ms to 10 ms) is achieved by an adequately low scanning rate or by repeated scanning.

Scanning electron beam annealing has the advantages of a constant electron energy and the capability of processing only desired portions. Because the temperature is below the melting point of the material, it is considered to be solid-phase epitaxial regrowth. In contrast to pulsed electron beam annealing, it is possible to repeat annealing or overlap partially annealed areas and maintain the annealing homogeneity across the entire wafer. Unlike pulsed electron beam annealing, scanning electron beam annealing maintains the doping distribution profile well.

Electron Beam Deposition

The most mature application of electron beams in semiconductor manufacturing is electron beam deposition or electron beam evaporation. During this process, atoms or molecules evaporated by direct heating from the electron beam are used to deposit a thin film on substrates. This has been the predominant method in the field of electron beam processing since its first successful application 40 years ago (10–12).

Electron beam evaporation is a vacuum coating process in which a directed vapor stream propagates from the evaporator to the substrate. The principle of electron beam evaporation is shown in Fig. 11. An electron beam evaporation system consists of a work chamber with a vacuum pumping system, a water-cooled crucible for the evaporant, an electron gun, a shutter, and a substrate along with fixtures and heating appliances. In contrast to conventional heating methods, the evaporant is heated by an electron beam that impinges directly onto its surface, and the majority of the kinetic energy in the beam is converted into heat. Therefore, the surface is brought to such a high temperature that it becomes the source of a vapor stream. The substrate to be coated is placed in this vapor stream and part of the vapor condenses on it as a thin film.

As can be seen in Fig. 11, it is necessary to place the substrate directly above the evaporant to achieve the highest deposition efficiency. This requires positioning the electron gun off the axis so that the gun does not block the path of the vapor steam traveling toward the substrate and so that the vapor steam does not enter the gun. Normally, the electron beam is bent 90° by a magnetic deflection field in an axial electron gun before it impinges on the evaporant. In a more advanced transverse gun system, a 270° beam bend is required.

The evaporation rate R depends on the molecular weight M of the material, the temperature T, and the saturated vapor pressure p and is given by (13)

$$R = 4.4 \times 10^{-3} \alpha p \sqrt{(M/T)} \tag{29}$$

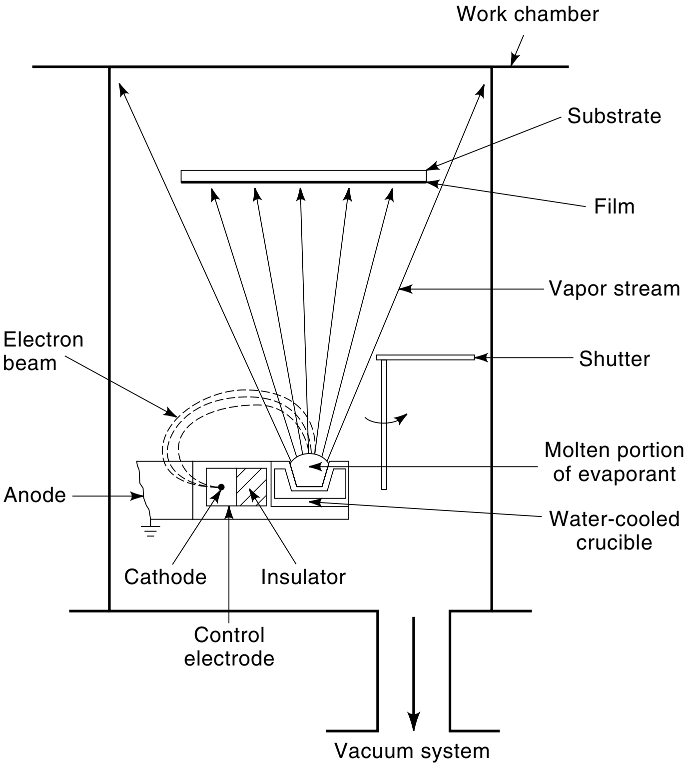

Figure 11. Electron beam deposition equipment with a transverse gun. In this configuration, the gun and crucible are combined into a single unit and the electron beam is deflected by an angle of 270°. It is fairly simple and compact compared with the so-called axial evaporator in which the gun is separated from and placed above the crucible.

where α is the evaporation coefficient, which depends on the material. The relationship between T and p is given by thermodynamics (Clausius–Clapeyron equation). Once the temperature T is known, the evaporation rate R can be calculated.

The relationship between the input power of an electron beam and the rise in the surface temperature of the evaporant is complicated. It involves the heat losses due to conduction from the evaporant to the crucible, the heat radiation from the hot evaporant, and interactions between the vapor cloud and the electrons. The thermal process described in the *Theory* section provides the basic tools for the analysis.

In the case of an alloy evaporant, the temperature rise of each element is the same. Therefore, elements with a higher vapor pressure are vaporized more rapidly than others. Consequently, the deposited film may have a composition different from that of the alloy. Additional measures may be needed to obtain a correct composition in the deposited films.

To control growth and thickness, the film thickness is usually monitored during the actual deposition process. There are various methods of film thickness measurement. The most commonly used techniques are based on the quartz crystal resonator and the ionization gauge. The quartz crystal resonator detects the change in resonant frequency due to the change in mass deposited on the quartz crystal. The ionization gauge detects the ionized vapor and residual gas molecules in the vacuum. Upon detection, the ion current originating from the vapor stream is transformed to an alternating current by a mechanical shutter and thus is distinguishable from the current due to the residual gas.

Evaporation by electron beam direct heating has many advantages over other heating methods. It can be applied to high melting point materials because the directly heated, vapor-emitting surface has the highest temperature of the evaporating device. It is a better alternative to filament evaporation when depositing materials are reactive to tungsten and tantalum, which are usually the heating elements directly contacting the materials. It is also the preferred method for obtaining higher purity films because reactions with crucibles containing the materials are avoided almost completely. In electron beam evaporation, high energy efficiency and highly accurate control are retained because the material is heated directly.

EVALUATION

Since electron beam processing was invented 60 years ago, it has spread widely into various industrial fields. It was invented for cutting materials and other machining purposes but also gained full acceptance in environmental control, chemical reactions, semiconductor manufacturing, etc. as a very useful processing method.

Besides the annealing and deposition processes previously mentioned, electron beam processing can also be used for alloying deposited films, consolidating metal coatings, ultrarapid heating and cooling, solute trapping, and zone refining in semiconductor manufacturing (14). Electron beam lithography is another major application of electron beam processing in semiconductor manufacturing which has also been extensively developed and widely accepted (15). All of these processes require applying relatively high energy to a well-defined area during a certain period of time. The unique format of the electron beam, a flux of easy control and well-shaped energetic electrons, matches the requirements very well. As the *scaling down* trend continues in semiconductor manufacturing, deeper involvement of electron beam processing is predicted.

The major attraction of electron beam processing is its well-controlled and well-shaped high-power electron beam generated by a carefully designed electron gun. Its applications span from melting large pieces of special materials in mechanics to patterning nanometer size features in microelectronics. Further development of electron beam processing will certainly present itself to other unexplored industries.

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ELECTRON DENSITY MEASUREMENT. See FUSION REACTOR INSTRUMENTATION.

ELECTRON EMITTER. See CATHODES.

ELECTRON FIELD EMISSION. See FIELD EMISSION.

ELECTRON, FREE ELECTRON LASERS. See FREE ELECTRON LASERS.

ELECTRON/HOLE MOBILITY. See ELECTRON AND HOLE MOBILITY IN SEMICONDUCTOR DEVICES.

ELECTRONIC BALLASTS. See HIGH-FREQUENCY LIGHTING SUPPLIES.