Fig. 1 - Novel THEVA E-vaporator

E-beam evaporation reloaded: increased applications

Electron beam evaporation constitutes one of the most economic and widely used coating techniques. A major drawback, however, is the limited applicability to simple oxide and metal coatings. Novel concepts and e-beam sources allow extension of the application range to a lot of vacuum heating processes and deposition of complex compounds comprising constituents with widely differing volatility.

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INTRODUCTION

Thermal treatment and heating are integral parts of most processes performed under vacuum. The span of applications is wide ranging from surfaces heating for cleaning, desorption and hardening, to melting of ingots, vacuum soldering and evaporation. Hence, the popular vapor deposition technique is just one facet of the more general theme of applying thermal energy to a certain volume of material to e.g. transfer it into the gas phase.

Compared to ambient heating the lacking gas atmosphere offers a unique opportunity for a directional transfer of energy. A beam of high energy electrons is easy to generate and to manipulate by electric or magnetic fields and can transmit energy over a considerable distance.

At first glance, the use of e-beam sources appears to be a relatively expensive and fancy way to produce heat. However, higher throughput and reliability can easily countervail the higher capital investment in the total unit cost account. Short cycle time results in a more efficient use of the equipment and long service life allows a high level of automation – both crucial ingredients to bringing down production costs.

As a consequence, e-beam evaporation is a widely used physical vapour deposition (PVD) processes for industrial-scale metal coating. However, the potential inherent to e-beam assisted processing has not been fully utilized so far. This may change with the introduction of a new class of handy e-beam sources that open up entirely new application windows.

ADVANTAGES OF E-BEAM HEATING

Compared to infrared (IR) radiation heating or lasers, an electron beam offers a variety of advantages:

- Impinging on a surface electrons are penetrating the material only a few microns before they are stopped. At a kinetic energy of a few keV, low energy secondary electrons and soft X-rays are produced in this process. The lion's share of their energy, however, is deposited in this very thin surface layer which is effectively heated irrespective of its IR–absorption. This facilitates selective annealing of surfaces and coatings (e.g. for hardening) without affecting the bulk of sample, and the small heat capacity accounts for very short cycle times.
- Sweeping the e-beam at high frequency allows an accurate definition of the heated area and energy is just applied where it is needed. Hence, compared to conventional IR-, induction- or laser-heating the overall energy efficiency is extremely high.
- The reaction and control of the e-beam is fast and since no inertia is involved heating can be switched on and off practically instantaneously. Consequently, there is no risk of damage due to overheating, e.g. when a process is on hold.
- The e-beam control can be synchronized or triggered by other parameters, e.g. the position of a moving workpiece, and allows integration into a complex process sequence.
- Eventually, the accessible temperature range does not depend on any crucible or heater material and can be chosen well above 2,000°C. Such extremely high temperatures facilitate high rate deposition and even quantitative evaporation of materials with low vapour pressure. Since no other materials are involved the purity of the source material is preserved throughout the entire process.

COMMON E-BEAM SOURCES

E-beam sources are commercially available in two standard configurations: linear e-guns and e-beam evaporators with 270° - beam deflection.

A linear e-gun produces an e-beam which is extracted from a heated tip or filament, focussed by magnetic lenses, and directed towards the area of application. This self-contained e-gun concept is appealing because the beam generation is completely separated and independent from the target. Unfortunately, these sources have been available at very high power level only – between 60-800 kW. Their main fields of application comprise industrial high volume metal deposition and e-beam welding.

In the much more customary power range of a few kilowatt the common configuration is a filament block attached to a crucible, where the e-beam is 270° - deflected into the crucible by a magnetic field. This is a very compact stand-alone evaporation unit which allows easy integration into an existing vacuum system. However, its compactness is at the expense of flexibility and lifetime. The capacity of the crucible is usually limited to a few cubic centimetres. Due to the short distance between filament and crucible in the long run contamination becomes a major issue, causing discharges in the high voltage section and limiting the lifetime of the filament.

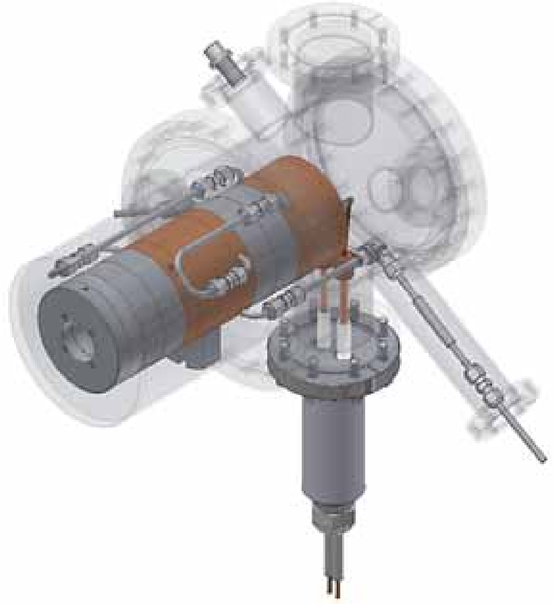

Fig. 2 - Flange mounted linear e-gun

COATED CONDUCTORS CALLING FOR NEW CONCEPTS

We encountered these restrictions, when developing a long-term continuous coating process for high temperature superconductors (HTS) on metal tapes – so called coated conductors (CC). HTS are very complex oxide compounds – in our case with the chemical formula $ReBa_2Cu_3O_7$ (Re = rare earth or yttrium). The tape coating process requires many hours of uninterrupted, stable operation and consumes kilograms of evaporation material. As a consequence, we ran into massive problems with the traditional 270°- deflection concept and eventually decided to develop an own linear e-gun for the power range below 10 kW. The outcome, the novel E-vaporator, constitutes a handy and modular tool offering all the advantages of the large scale, industrial linear e-guns at a reasonable power level which is sufficient for most vacuum processes.

This downsized linear e-gun can be flange-mounted as depicted in Figure 2 and placed below and far away from the evaporation crucible. This arrangement saves the filament and the high voltage leads from contamination and prevents discharges that can lead to a breakdown of the power supply. The electron beam is easily deflected inside the vacuum chamber by a separate magnet and directed to the desired target area. The electron optics allows scanning frequencies >400 Hz and accurate beam positioning and shaping.

This concept offers complete freedom of designing the crucible. Shape, size and movement of the heated target area can be custom designed to address challenges such as complex oxide coating or surface hardening of passing by tools such as drills or blades.

The evaporation and deposition of oxides usually involves a relatively high background pressure of oxygen reducing the filament life. In this respect, too, the large distance between filament and crucible, where oxygen is generated due to thermal decomposition, turns out to be beneficial. To further enhance lifetime the closed e-gun design offers an additional differential pumping option for the filament. Hence the reactive background pressure in the processing chamber can be chosen in order of magnitude higher than usual.

Fig. 4 - Crucible E-vaporator with double wire feeding

QUANTITATIVE EVAPORATION OF COMPLEX COMPOUNDS

As mentioned above, HTS are complex oxides containing constituents with strongly differing volatility. E-beam heating of a single pocket filled with HTS material would immediately result in decomposition and preferential evaporation of most volatile elements. As a consequence, the vapour composition would change with time.

The clue to preserve the stoichiometry of the source material in the vapor and to transfer it to the growing film is quantitative evaporation which may be considered a kind of "continuous flash evaporation". This can be realized by a water-cooled copper turntable extracting granulate of the mixed oxide material from a funnel and delivering a trace of this powder to the hot e-beam heated area, where it is completely – i.e. quantitatively – evaporated[1]. This principle is sketched in Figure 3 (the feeding funnel has been omitted for reasons of clarity). After a short initial setting time a steady state between incoming and evaporating material is established and the metal composition of the powder is transferred to the film without additional in-line composition control. The overall deposition rate is directly proportional to the feeding rate of the material, i.e. the rotation speed of the turntable and the geometry of the trace.

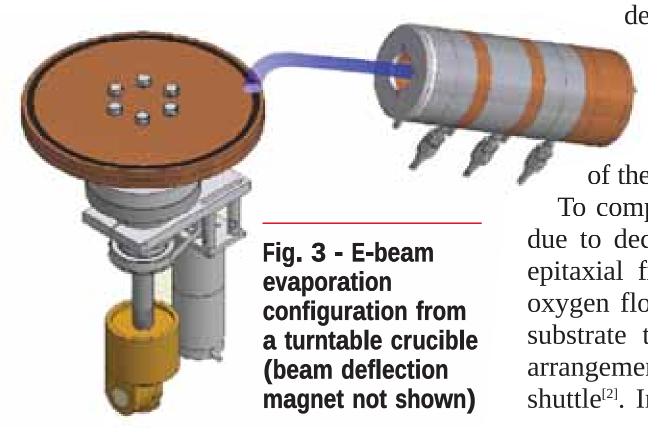

Fig. 3 - E-beam evaporation configuration from a turntable crucible (beam deflection magnet not shown)

To compensate the loss of oxygen due to decomposition and to enable epitaxial film growth, an additional oxygen flow is supplied close to the substrate tape by a moving nozzle arrangement – the so-called oxygen shuttle[2]. In this way, several tens of meters of high quality CCs, carrying currents up to 400 A/mm^2 at 77 K, have been successfully manufactured by prototype equipment.

ALLOY COATING WITH LOW SUBSTRATE HEAT LOAD

Eventually, the coated conductor tape requires a high rate Ag/Au or Ag/Cu alloy coating to realize electrical contact. Since the tape is temperature sensitive in that stage overheating becomes an issue and heat input onto the substrate has to be minimized.

To address this point, we designed a very compact evaporation source, where a small tungsten crucible is placed directly on top of the e-beam source and heated from the bottom. Continuous wire feeding allows evaporation of kilograms of material from a source volume of merely a cubic centimetre. Applying sufficient heating power, the incoming wire is smoothly evaporated without splashing or spilling over of the crucible. Alloy coating is straightforward in this arrangement and is realized by a double wire feeding as shown in Figure 4.

In general, there are four mechanisms that contribute to the substrate heating:

- heat conductance in the process gas (e.g. for sputter deposition)
- radiation heating from the hot source
- kinetic energy of the vapor species
- vapor condensation from the gas phase

Since evaporation does not involve any processing gas, the first mechanism is absent and the second is minimized due to the small crucible area and the large distance to the substrate. Compared to sputtering processes, where atoms of the deposit can carry a considerable amount of kinetic energy, the thermal energy of evaporated species is relatively small. Hence, at high deposition rate the condensation mechanism is dominating. It is proportional to the mass transfer and independent from the technique that generates the vapor.

In summary, the compact crucible geometry minimizes radiation and results in the lowest possible substrate heating of all PVD processes. Consequently, even very heat sensitive substrates are accessible to high rate metal deposition.

CONCLUDING REMARKS

The need for an economic and long-term stable vacuum deposition process has led to a rediscovery of e-beam evaporation. A novel e-beam source covering the power range between 1-10 kW combines the advantages of large industrial-scale systems with cost-effectiveness and flexibility of use. These stand-alone e-guns address a large variety of vacuum heating processes from annealing and hardening, to vacuum soldering and evaporation. The advantages are strikingly demonstrated in the successful fabrication of HTS coated conductors which comprise complex oxides as well as alloy coatings – material classes that were commonly regarded inaccessible to economic e-beam vapor deposition until recently.

PATENT LITERATURE

[1] *EP 1558782*
[2] *DE 19631101*

Fig. 5 - Vacuum coating system (optional)

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Fig 6 - Coated conductor tape (optional)