IJD and PLD a comparison

Technical insights

Version 1.10

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Ionized Jet Deposition system and method

Ionized Jet Deposition (IJD) belongs to the Physical Vapor Deposition (PVD) methods. It uses pulses of energy carrier to rapidly transfer energy quanta to a solid state target causing the generation of non-equilibrium plasma plumes of its material and fast expansion of plumes towards the deposition substrates. Apart of the essential nature of the energy quanta carrier **the process of plasma generation and expansion is almost identical to that of Pulsed Laser Deposition (PLD) method.**

The experimental and theoretical starting point for development and up-scaling of the IJD goes back to 1979 paper of Christiansen and Schultheiss [1] on pseudo-spark particle generation and the further Schultheiss works of mid and late '90 [2 - 5] on channel spark deposition. However, the full and detailed understanding of the electron pulsed beam generation process and, hence, the ability to fully control the process and to scale it up to the industrial demands are results of the proprietary research of Noivion, Srl., originating from the advanced studies of channel spark discharge and Pulsed Plasma Deposition (PPD) by Nozar et al [6 - 10].

The applications of IJD to the deposition of perovskite materials generally and high-Tc superconductors especially started and were supported by early and preliminary studies performed at late '90 and beginning of 2000 and published by Jiang, Dediu and Nozar et al [11 - 21].

Basic principles

The description of the IJD system and the method is published in the Patent WO2013186697 [22] and in the next explanation this source will be followed.

The principal parts of the IJD head are reported in Fig. 1.

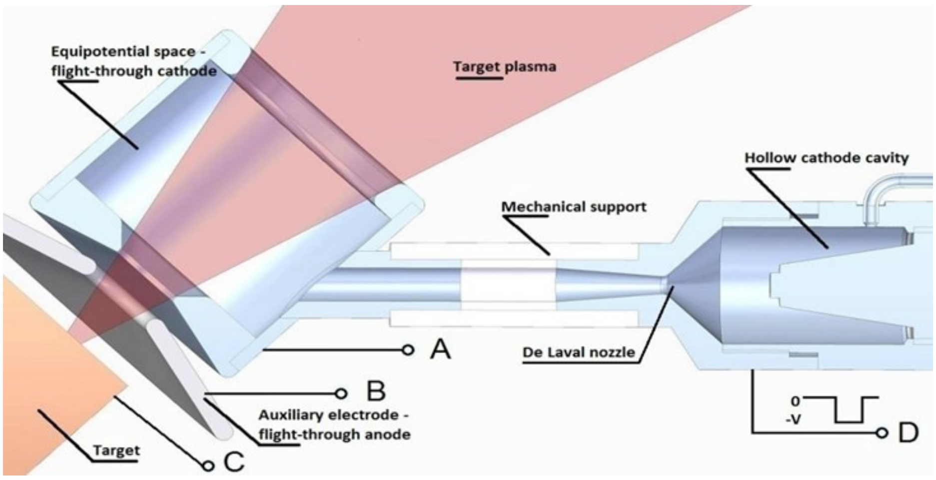


Fig. 1: Schematic picture of the IJD head.

The IJD head is composed of two main parts, namely the flight-through cathode (in Fig. 1 leftmost part) and the plasma trigger (in Fig. 1 rightmost part). The trigger may be constructed in many ways, however, in Fig. 1 the one most used and based on hollow cathode cavity is depicted. The trigger and the main flight-through cathode are connected through the de Laval nozzle. De Laval nozzle ensures that the gas fed into the trigger cavity from outside (from far right in the Fig. 1) is propagating in the direction of the flight-through cathode and further towards the target without dispersion in space even in the conditions of the surrounding vacuum.

The generation of the electron pulse (electron packet) starts with the charging of the flight-through cathode and, simultaneously, the trigger system to the negative working potential (in the order of thousands of volts). After the charging the system is in a stable state without the tendency to the discharge. Therefore, the positive voltage impulse to the central trigger electrode of the order of one kilovolt is fired and such event results in the vacuum break down and an auxiliary discharge in the trigger cavity generating a small amount of dense plasma.

This plasma plume is expanding and propagating through de Laval nozzle into the flight-through cathode and creates, in its center, a region of slightly positive potential with respect to the cavity wall. From this point onwards the flight-through cathode behaves as a hollow cathode and an electron generation takes place [23].

The process of auxiliary plasma expansion into the flight-through cathode is depicted in Fig. 2.

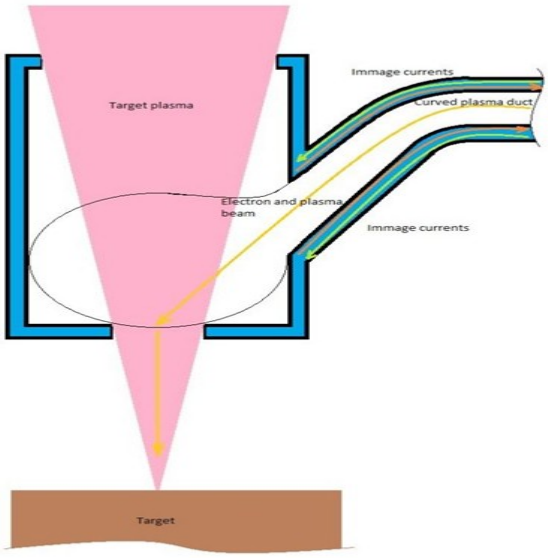


Fig. 2: Schematic of the auxiliary trigger plasma propagation towards the flight-through cathode and the positive potential generation process.

During the period of the hollow cathode electron generation the dense packet of the electrons is created, temporarily stored in the flight-through cathode at the cathode potential. These electrons are then released in the form of the dense electron packet and accelerated towards the target by cathode - target potential difference (the target is kept at zero potential).

Upon the arrival of the electron packet to the target surface the electrons transfer their energy into the target material through mutual collisions among the electrons and target ions creating a dense plasma plume of the target material. The target material plume expands in opposite direction (not only) to the incoming electrons towards the flight-through cathode, it passes through the cathode (hence the “flight-through” cathode) and it propagates further towards the sample substrate. There the target material is then deposited.

As the process of the energy transfer from the electron packet to the target is extremely fast high power one and, hence, highly non-equilibrium process, the target material transfer is independent on bonding energies of the ions in the target and the stoichiometry of the target components is maintained even if otherwise the components are melting incongruently.

Fig. 3: IJD head mounted on the head support

The actual form of the supported IJD head is depicted in Fig. 3 and the function hereof is shown in Fig. 4.

In Fig.3 a IJD head together is presented with de Laval nozzle and trigger cavity (both inside the IJD head) are on the left side of the system. The central white tube is an isolating ceramic support tube containing the gas feeder tube and the trigger electrode contact wire. On the right part of the system the external box containing electronics and gas control elements are located.

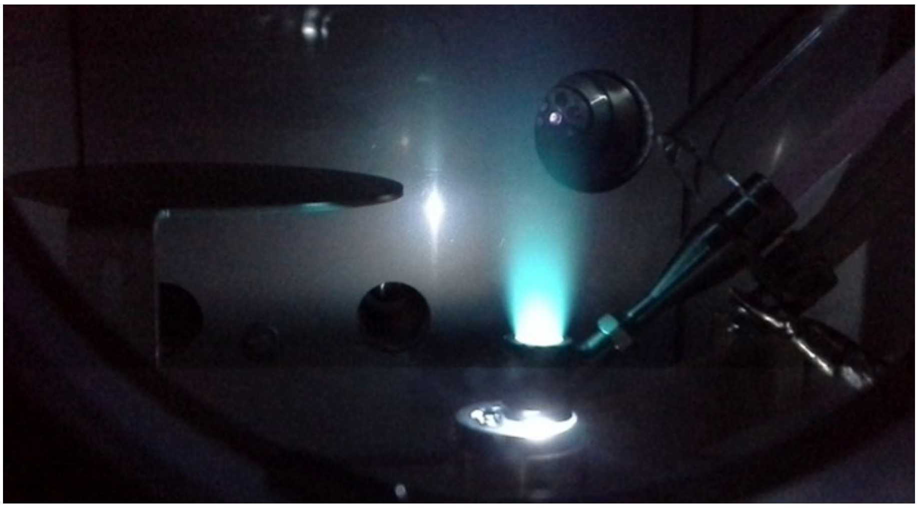


Fig. 4: IJD system in function

The Fig. 4 shows the IJD head in the process of the target ablation and plasma plume expansion towards the sample substrate. The target (in this case Molybdenum) is the illuminated cylinder at the bottom of the picture. The IJD flight - through cathode can be seen as the dark cylinder in the middle and the expanding plasma plume as the illuminated cyan plume above. A shutter controlling the precise time of the deposition is located on the far left side of the chamber.

Comparison of IJD and PLD

Ablation of the target material (removal of the material from the target surface and its transfer to the sample substrate) by PVD pulsed energy processes follows a similar pattern: the pulse of energy mediated by different physical carriers arrives at the target surface and, in an extremely short time, it is absorbed by superficial and shallow sub-superficial part of the target.

The irradiated part of the target is heated in fast non-equilibrium process which allows only a partial transfer of the energy to proceed inside the target body. A major part of the energy contained in the pulse is converted to the internal energy of the target surface ions which change the state from the solid to the plasma one. The initial very high-density plasma speck gradually expands in all directions from the origin, however, mainly in the direction perpendicular to the target surface ($\approx \cos^{\beta} \alpha$ where α is measured from the perpendicular to the target surface and β takes values between 2 - 4 according to different authors).

Occasionally the thin layer of melted material can be found in the ablation spot between the plasma plume and the solid target material. In such case the back pressure applied by the plasma plume may push the liquid out of the spot and the melted material may reach the sample substrate in the form of the particulate.

A schematic description of the ablation process is shown in Fig. 5 and 6.

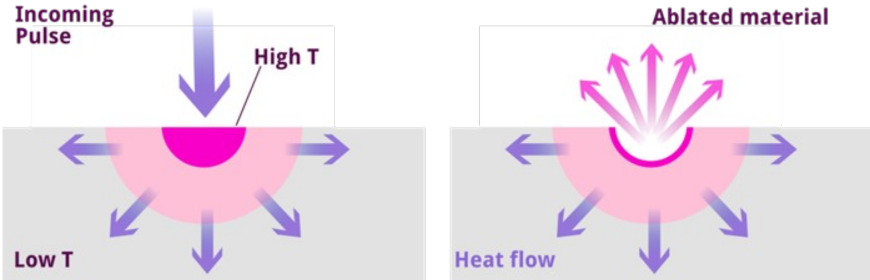


Fig. 5: Principles of the pulsed energy ablation

In the case of IJD the energy carrier is the pulse or packet of energetic electrons, while PLD is based on the carrier in the form of the light pulse.

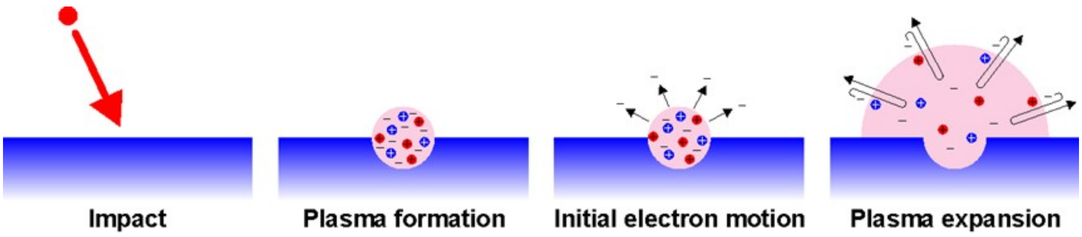


Fig. 6: Schematic picture of the plasma plume development.

Even if the basic **ablation process is similar for both methods, there are some important differences** originating from the diverse nature of the energy carriers.

The plasma plume is created through the ionization and scattering of charged particles - electrons - with the target ions in the case of IJD **instead of strong electric field in the case of PLD.**

The laser light is strongly absorbed by generated plasma heating it and, therefore, it is advantageous to apply very short laser pulses to increase the efficiency of the ablation process in the range of nanoseconds and even pico- and femtoseconds. **No such limitation is imposed on the electron packet of the IJD.**

Electrons pass the plasma without significant absorption or energy exchange and the ablation pulse can be much longer (in tens or hundreds of nanosecond) not losing the efficiency of the ablation and not lowering the deposition rate.

The amount of the deposited energy onto the target surface depends critically on the angle at which the energy carriers arrive at the target surface. There is always some part of energy carriers which are reflected away from the target surface and the amount is increasing with increasing the angle α (measured from the direction perpendicular to the target surface). **In the case of electrons, the critical angle at which all of electrons are scattered out is 45° while in the case of light it depends on the optical properties of the target surface-vacuum interface.**

Therefore, **the IJD head is constructed in such way that the electron packets are hitting the target surface perpendicularly ensuring the maximum efficiency of the process** (see Fig 1, 2 and 4).

PLD owing to the nature of the energy carrier - light - shows some type of problems if applied to the materials transparent for type of the light used which is manifested in substantial lowering of the ablation efficiency and of the deposition rate. The electrons do not depend on transparency of the target and due to the presence of the plasma near the target surface the electron packet is not strongly dependent on electrical properties of the target either (plasma presented at target helps to discharge the target if needed).

All PLD and Pulsed Electron Deposition (PED) methods other than IJD suffer from the strong contamination of the sample surface from the particulate mentioned above. Such particulate may be produced by the process described above but also by the target subsurface explosion of the plasma ball caused by steep increase of the temperature and pressure in the ablation region. This explosion carries away the solid particles of the debris created by the mechanical stress presented on the edge of the ablation spot. There are several more or less efficient methods how to mitigate this tedious effect in the case of PLD (see e.g. Fig. 7)

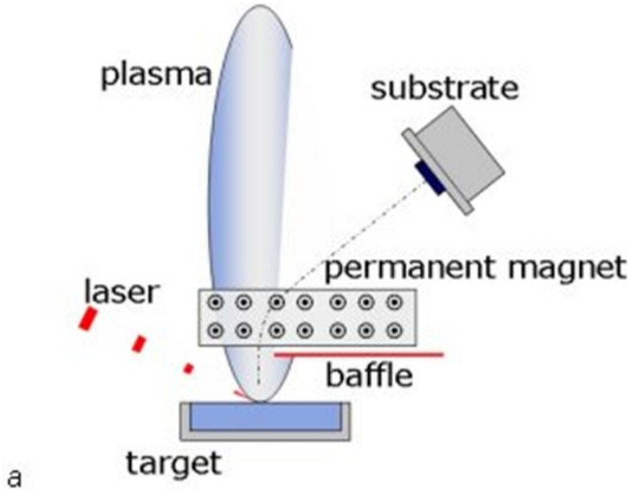


Fig. 7: Schematic picture of the particulate filter for PLD created combining the simple baffle with magnetic field plasma deviation towards the sample substrate.

However, it is well known fact that the plasma plume is propagating mainly perpendicularly to the target surface (or, in any case, at small angles α) whereas the particles are expanding at large angles α. Therefore the **IJD head is constructed in such a way that the particles escaping at larger angles α are directly mechanically separated from the plasma flux** (see Fig. 8).

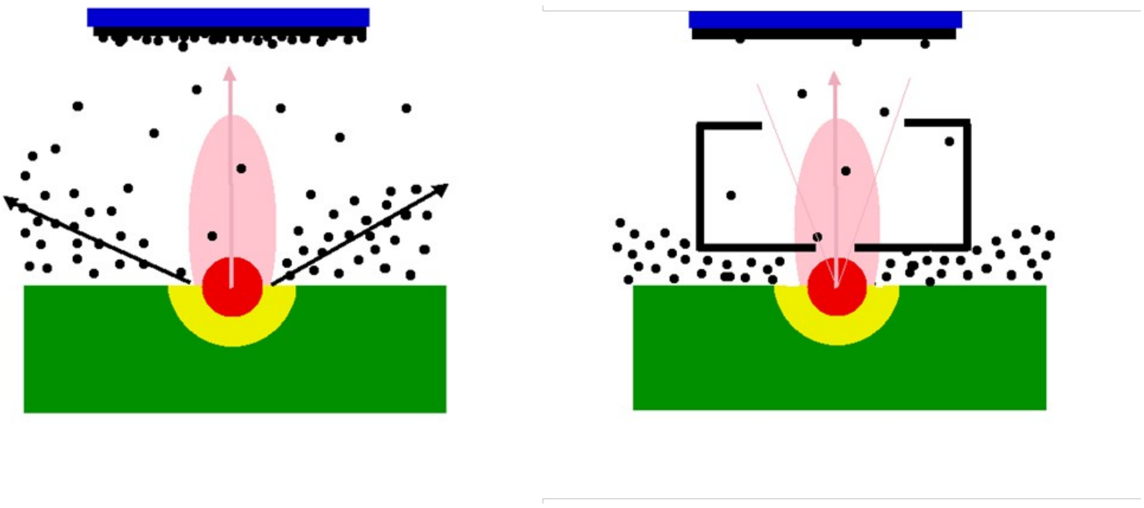


Fig. 8: Schematic picture of the particles propagation in the PLD case (left) and IJD case (right).

The traces of the larger particles are well seen at the lower part of the Fig. 9, where YBCO target is ablated and the material is deposited on the substrate fixed above IJD head at the upper part of the image.

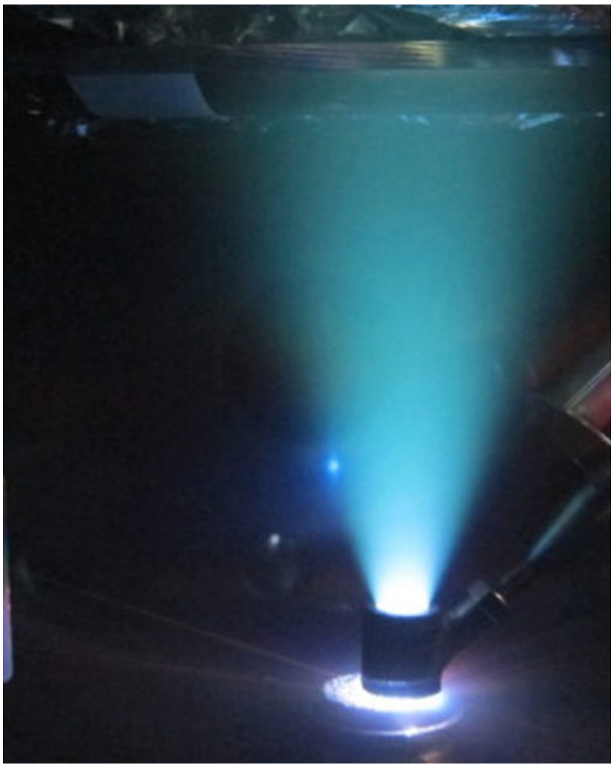
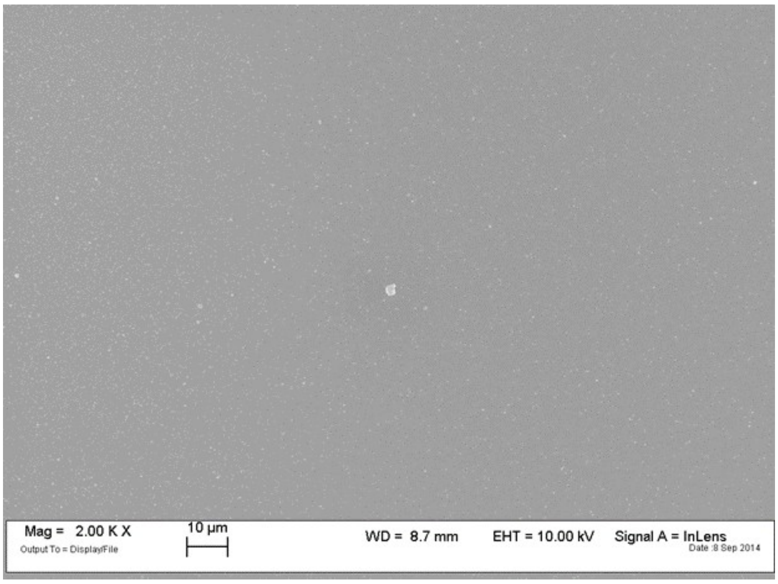


Fig. 9: Example of the YBCO ablation, at the lower part of the picture the traces of the larger particles can be observed. The particles are deviated by the geometrical shape of the IJD head from their way to the target (upper part of the image) and leave the space between the IJD head and target laterally.

However, **IJD offers an additional feature for the particulate suppression - lowering the acceleration potential and increasing the pulse repetition frequency the clean flat surface samples can be prepared** (Fig. 10)**.**



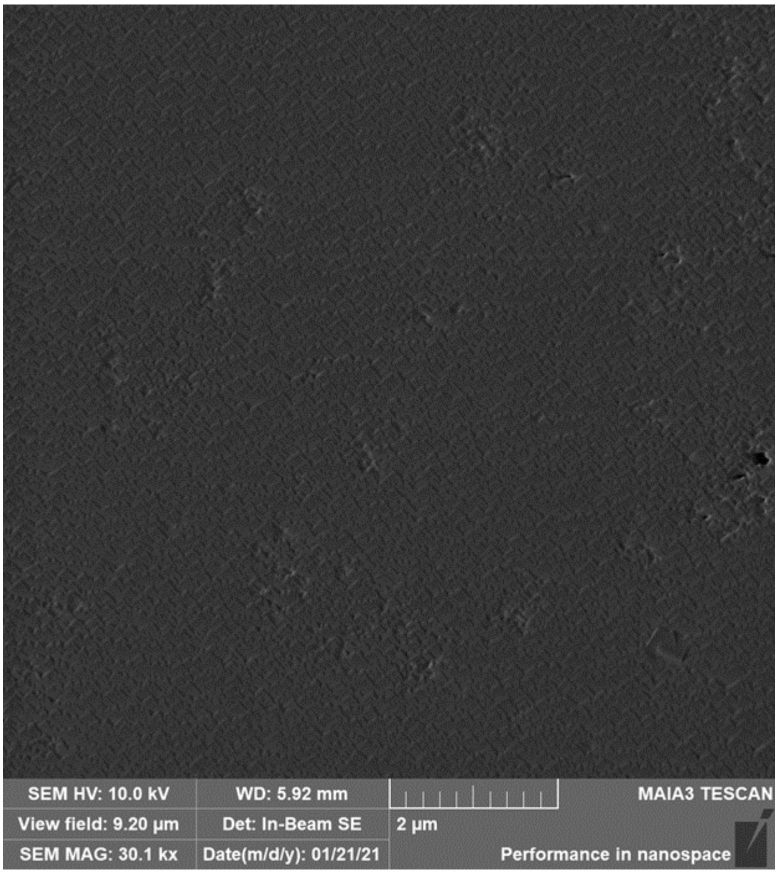


Fig. 10: IJD deposited ZrO2 on Si substrate (upper image) and YBCO on textured metallic substrate (lower image, triangular features correspond to the substrate texturing)

Similarly to the PLD also in the case of IJD some reactive gases may be introduced into the deposition chamber just to control the chemical reactions and sample composition during the deposition. As for IJD the gas can be introduced directly to the deposition chamber. Such process is identical to the PLD process. However, there is another possibility - to introduce the working gas through the trigger and IJD head, the gas can be almost 100% ionized during the process and in this state mixed with the target plasma plume. The ionized gas is then extremely reactive (which gives possibilities e.g. to deposit metal oxides or nitrides ablating pure metal targets in oxygen or nitrogen gas passing the IJD head, other reactive gases also possible).

One very important advantage of the IJD process is the fact that once developed the deposition process for one IJD head it can be applied to the arbitrary number of IJD heads obtaining the same results. Therefore it is possible to assemble the various amount of IJD heads in the single row and in combination with the roll-to-roll process to create arbitrary wide and arbitrary long surfaces covered by deposited material maintaining the layer quality and homogeneity (thickness). Combining the IJD heads in different directions even complicated shapes can be covered by deposited material.

IJD basic process parameters

Regarding the process parameters some of them are identical in the nature for both PLD and IJD some others are just analogues:

Single pulse energy E_p	from mJ range up to 15 J
Pulse repetition frequency f_p	0 - 500 Hz (max. actual value for high-end single head system)
Pulse duration t_p	50 - 450 ns (depending on the energy storage capacity)
Maximum single pulse power density W_p	10^{10} - 10^{11} W/cm^2
Rated AC power supply power W_{ac}	2,5 kW (max. actual value for high-end single head system)
Deposition chamber internal gas pressure	5×10^{-4} – 2.4×10^{-3} mbar (in O_2, recalibration for other gases needed)
Sample temperature at deposition	RT - 950 °C (max. actual value for high-end single head system)
Multilayer deposition	yes, sequential from different targets using single IJD head or sequential/simultaneous from different targets using higher number of IJD heads

Conclusion

It can be concluded that the IJD system is a competitive alternative to PLD **much more versatile** in respect to the amount of materials suitable for deposition.

- IJD **exhibits flexible and controllable parameters** for fine tuning of the deposition processes.
- IJD is **faster in deposition rate.**
- IJD is **ready for industrial up-scaling** comparing to the PLD systems.
- IJD system **can prepare the same quality (if not higher) layers as PLD for the fraction of the costs.** (acquisition and maintenance costs of the IJD system represents only small fraction of PLD system costs.

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