ACTUATORS FOR NANO-POSITIONING IN VACUUM

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INTRODUCTION

The semiconductor industry is a highly interesting field for electrical drives by the rising demands in the last decade. Nano-meter accuracy was already proven for stages 20 years ago, but nowadays this is requested also for semiconductor equipment with accelerations of more than $10m/s^2$ during 40% of the time. The dynamics of the mechanics has to be solved first, including vibration isolation. Subsequently follows the actuators with as main items their control behaviour, heating and mass. Vacuum compatibility is added recently. So, clear challenges for electrical drives.

THE INTENTION OF A SHORT STROKE ACTUATOR

Before going into details concerning actuators some description of the application. The stages in semiconductor industry have to realize a stroke of at least 12 inch of modern wafers, so linear motors has to be applied. It is hard to realize a linear motor with that stroke, a force level of e.g. 1000 N, which realizes a position accuracy of nano-meters running at e.g. 1 m/s. Even when nearly ideal moving coil motors are used one meets the motor gain variations of more than 2% and the imperfections of power electronics of a linear commutating motor. One proven way to solve this is to stack on top of the linear motor a short stroke actuator with a stroke of several millimetres and a good predictable gain, expressed in Newton/ampere.

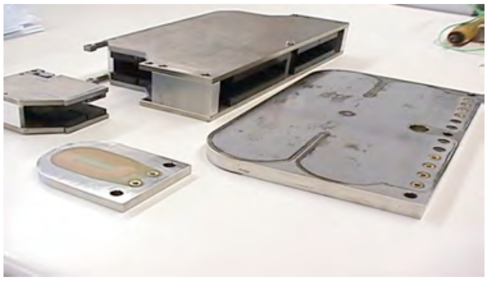

FIGURE 1. A short stroke actuator.

DESIGN

A short stroke motor is in fact nothing more than a bunch of wire, permanent magnets and some iron as shown in figure 1.
But a stage requires

- positioning in two directions, X and Y
- very small forces in the Z-direction to prevent going out of focus in e.g. lithography
- gain deviations smaller than 1%
- as less moving mass as possible
- nearly no heat transfer to the stage or environment to prevent thermal gradients and laser interferometer inaccuracies.

The fifth point cannot be separated from the others, because the electrical loss for a given force is the result of electromagnetic design of the actuator. The design can be done with e.g. a 3-D Finite Element Modelling package or by means of an analytical approach as given in [1], [2] and [3].

The reduction of loss has also as positive effects the lower power amplifier specification, smaller cable slabs and less effort to remove the heat out of the equipment by water-cooling, the only option in vacuum applications. It simply means lower costs of ownership and it should not be amazing that the costs of high-grade NdFeB magnets can be accepted.

Of course one should know the effective force before a design can start. The loss follows with the help of the motor constant K_m [$N/\sqrt{W}$]. This motor constant is equal to the ratio $K/\sqrt{R}$, with K [N/A] as the force constant and R [Ohm] as the coil resistance at the conductor temperature intended, which rises with 0.4%/Kelvin.

The losses decrease with rising K_m, so K should high (apply strong magnets) and R as low as possible.

THE COOLING

In [4] a winding technology is described leading to as much copper as possible, called the orthocyclic winding technology and this allows the thickest wire as possible for a given coil section by stacking the wires nicely distributed, see figure 2 and 3. A copper space-filling factor of 70% is obtainable, whereas 50% is obtained with an uncontrolled winding process. This has as additional advantage that the thermal resistance within the coil decreases with a factor nearby 2. This approach limits the internal coil temperature (usually near 100 ºC) and the resistance rise (the 0.4%/K mentioned before).

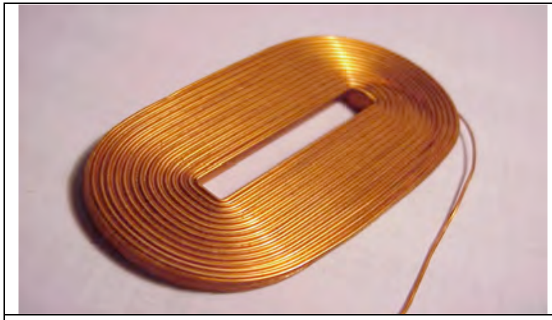

FIGURE 2. An orthocyclic wound coil.

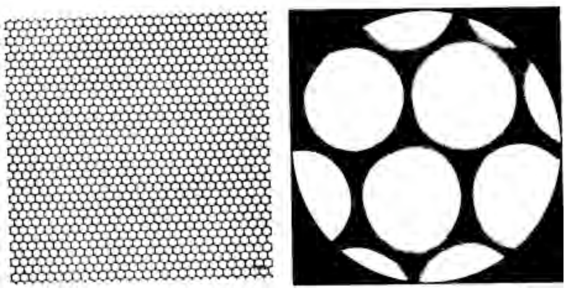

FIGURE 3. A typical cross section.

The current I determines the force level and a design rule is that a current density $J=3\ \mathrm{A/mm^2}$ in the copper does not require forced cooling. In semiconductor equipment more than 10 $\mathrm{A/mm^2}$ is usual, so forced cooling is needed.

Hollow conductors for internal cooling, as used in power plants, are not applicable, because their minimum dimensions do not belong to the 6 to 10 Ampere being attractive for the cable slabs in this type of equipment. It is further the nature of this type of actuators that coils are flat, so surrounding the coils with a water channel is less attractive as a consequence of the long thermal path through the coil. The ideal solution is to enclose the coils with an electrically non-conducting ceramic with good thermal characteristics, like Aluminium-oxide and Aluminium-Nitride and to fill all holes by potting. But costs of the ceramics and cracking problems stimulated us to find other solutions. Until now a stainless steel plate, provided with openings for the coils can do the job. Initially stainless plates covered the coils to transfer the heat to the water channels drilled in the stainless steel body. A development of the last years is to cover the coils on each side with two thin stainless steel plates with a water channel in between.

Stainless steel is applied for several reasons. The first argument is that the material should be non-magnetic to prevent forces towards the magnets. This requires a careful selection of the type of stainless steel and sometimes even annealing when drilling or welding made the material again magnetic. The second argument is the relatively high specific resistivity. A material as Aluminium will give rise to eddy current damping, what will be noticed as a viscous damper between the long stroke linear motor and the stage. This damper like behaviour will transfer the micron position inaccuracies of the long stroke motor into unwanted forces acting on the stage. In the case this damping of the cooling plates remains unacceptable even with stainless steel one can insert local slits to reduce the eddy currents or apply Titanium for its even higher resistivity.

The thermal contact between the potted conductors and the cooling plates can be guaranteed with an elastic glue, capable to withstand deviating thermal expansions. A thinner the glue layer is an advantage looking to thermal resistance, but a risk looking to deviating thermal expansions and high voltage safety requirements when voltages higher than 50 Volt will be applied. One cannot rely on the wire insulation only, because the industrial standards allow uncoated spots on the wire. A minimum of 0.1 mm glue should be taken into account.

The potting compound and glue to fix the cooling plates should be selected partly on their specific thermal resistivity, because even the thin layers are recognizable as significant thermal resistances.

THE CONDUCTORS

Until now we assumed insulated round copper wire as the conductors. Copper wires with a square cross section did not give a significant improvement. Attempts were done to use paper insulated copper foils to reduce the internal thermal resistance and increase the conductor space-filling factor. However too often partly short-circuited turns were found after flattening the coils with diamond grinding to obtain a flat surface to be contacted with the cooling plates. Experiments with Aluminium foils with an oxide layer are promising (see figure 4).

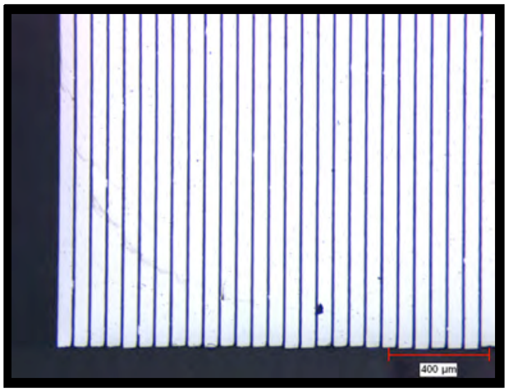

FIGURE 4. Aluminum foils based coil.

THE MAGNET STRUCTURE

As stated before we do not hesitate to apply high-grade magnets as NdFeB to improve the performance. Originally we only applied the simple magnet structure in Figure 5.

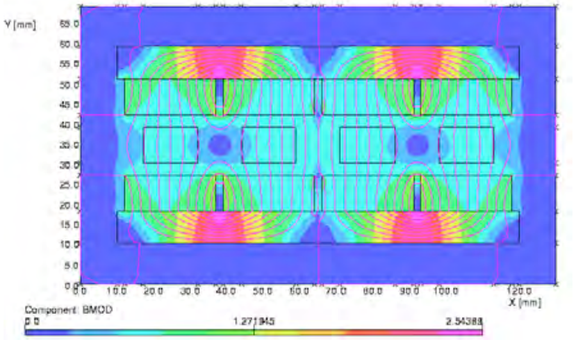

FIGURE 5. A 2-dimensional analysis of a short stroke actuator.

The rising demands stimulated us to apply the so-called Halbach magnet structure, see figure 6. Between the main magnets a magnet is added with its magnetization perpendicular with respect to the main magnets. This trick enhances the field strength in the coil area and reduces the flux density in the back iron.

The thickness of the back iron is partly determined by the first mechanical resonance frequency, which should not introduce control instability. With appropriate mechanical fixation one meets as next limit the magnetic saturation of iron near 2.05 Tesla, when one reduces the back iron thickness. When mass reduction of the yoke has got a high priority one can apply CoFe with a saturation level of 2.15 Tesla and reduce the back iron thickness locally where the magnetic flux density does not reach saturation.

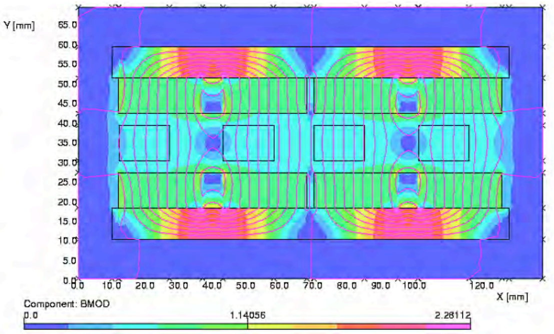

FIGURE 6. A 2-dimensional analysis of a short stroke actuator.

Nano-meter accuracy to be realized in milliseconds requests a very predictable motor constant K. For the magnets does this mean that their strength should be well defined. The only reliable way to determine the strength of magnets is based on a flux measurement with a Helmholz coil set, giving the magnetic moment of the magnet involved, see [5]. The magnetic moment is equal to the magnet volume times the magnetization. The bare magnet dimensions (so, without coating) have a tolerance of e.g. 0.1 mm in the plane perpendicular with respect to the magnetisation and 20 micron in the magnetization direction.

A more serious point is the standard tolerance of 5% on the magnetization strength. This can be reduced to 2% by using only the middle part of the basic big magnet blocks. What remains here after is selection. Additionally one should analyse the consequences of a spread of 5 degrees on the magnetization angle, the positioning of the magnets on the back iron, the tolerance on the distance between the opposing magnet yokes and the tolerances on the magnet coating. All these factors limits the predictability of the actuator performance and so control loop tuning remains required to reach nano-meters in milliseconds.

Fixing the magnets to the back-iron is done with glue and this is a treat for high vacuum. Adding to this the narrow slots between Halbach magnets means that the magnets start to be a cleaning issue. A proven solution is to cover the magnets with a glued thin steel plate of e.g. 0.1 mm to prevent vacuum contamination. Easy cleaning and open surface limitation are golden rules in high vacuum technology and we obey these rules in this way. The consequence of 0.1 mm stainless steel is limited when one considers a usual air gap of 0.5 to 1 mm in this type of actuators needed to prevent a severe alignment during assembly.

CONCLUSION

The design of short stroke actuators for high vacuum conditions is not adding much complexity when one starts with high performance actuators. Enclosing the coils with stainless steel as heat transfer medium was known and magnets can be covered with stainless steel without severe consequences.

REFERENCES

1. Compter, J.C., Hol, S.A.J., Lomonova,E., Lorentz actuators for nanometer accuracy, *Euspen Conference 2002:*49-53
2. Compter J.C., A planar motor with electrodynamic propulsion and levitation under 6-DoF control, *Proc. Of the 4th International Symposium on linear Drives for Industry Applications, LDIA 2003, 8-10 September 2003, Birmingham, UK*
3. Compter, J.C.; Lomonova, E.A.; Makarovic, J., Direct 3-D method for performance prediction of a linear moving coil actuator with various topologies, S*cience, Measurement and Technology, IEE Proceedings, Volume 150, Issue 4, 2003: 183-192*
   Volume 150, Issue 4, 3 July 2003: 183– 191
4. Lenders, W.L.L., The Orthocyclic Method of Coil Winding, *Philips Technical Review, Vol. 23,1961/62, No. 12*: 365-379
5. Compter, J.C., van der Veen, J.L.F., Magnet analysis with a Helmholz coil set, S*cience, Measurement and Technology, IEE Proceedings, Volume 150, Issue 4, 2003:177-182*