Principles of Electrostatic Chucks

7 — Frequently Asked Questions; Applications

Overview

In these pages are answers to most of the questions we are asked about electrostatics. Please contact us for more information if you don't find answers to your questions.

Why Electrostatics … and Basic Operation

Cleanliness, reliability, and uniformity...

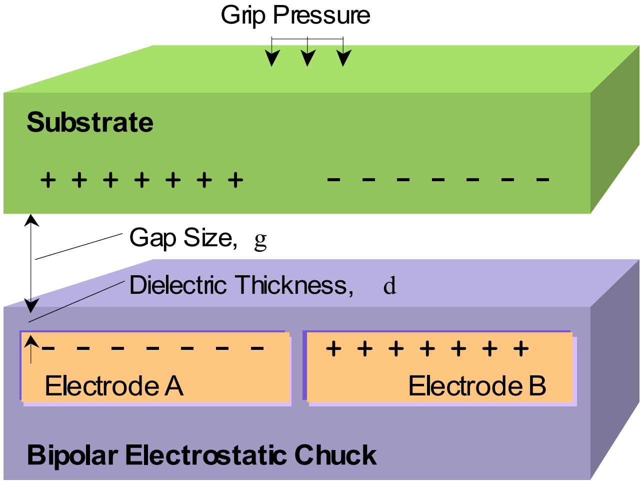
- No edge exclusion or plasma edge effects due to gripper fingers, rings, etc.
- Clamping to allow backside gas for temperature control
- Clamping to resist inertial forces under robotic motion
- Flattening of substrates for lithography, ion implantation
- Reduction of particle generation due to elimination of frontside contact
- Uniformity of rf and thermal contact to baseplate
- Reduction of wafer and clamp breakage, compared to mechanical clamps
- Reduction of particle generation, reliability improvement from fewer moving parts.

How electrostatic gripping works - conductive substrates

- Opposite charges attract.
- Wafer charges redistribute only on substrate underside … Zero lateral electric field on the substrate top surface while gripping.
- Grip force is proportional to charged plate area, so is calculated as a pressure
- A non-conductive dielectric between a monopolar electrode and a conducting substrate yields a grip pressure (in Pa) of

$[\varepsilon_0] [V\kappa_r / \{d + \kappa_r g\}]^2$ where

$\varepsilon_0 = 8.85.10^{-12}$,
V = electrode - substrate voltage,
κ_r = dielectric constant,
d = dielectric thickness, and
g = gap size
(from dirt, warpage, etc).



Thus, if $\kappa_r \sim 10$ (alumina), a gap 1/10 of the dielectric thickness will decrease grip pressure by a factor of 4.

The figure illustrates a bipolar chuck for which the above V would be half of the voltage between electrodes A and B; for symmetric electrodes $V = [-V_A + V_B] / 2$. The substrate potential is centered at the average potential, $V_S = [V_A + V_B] / 2$.

Coulombic vs. Johnsen-Rahbek (J-R) Attraction

The above assumes little dielectric conduction; the “Coulombic” mode. However conductive effects dominate after an RC time-constant delay for the dielectric-substrate equivalent circuit. Some dielectric time constants are less than a second; others hours. When conduction dominates, voltages develop laterally across the chuck surface, thus the chuck-wafer voltage drop varies. This voltage drop can reach the field emission/arcing limit. Thus regions of very high attraction adjoin regions of zero attraction. Very high surface-averaged grip pressures can be attained in this “J-R” mode.

Electrostatic Forces, and Comparisons with Vacuum Chuck

- Electrostatic clamp pressures generally attainable with Coulombic chucks are 4 - 26kPa (30 - 200 Torr). This is 1000 times the pressure due to a silicon wafer weight (wafer weight pressure is typ. <17 Pa = 130mTorr).

Higher pressures are available from J-R chuck styles.

- Vacuum clamp forces (for use in atmosphere) are ≤ 100kPa (760 Torr).
- Electrostatics are generally more expensive than vacuum clamps. However vacuum clamps can cause distortion, charge buildup, and be difficult to clean, so electrostatics can be useful in air, in competition with vacuum clamps.

Do electrostatics work in air and water?

- Both vacuum and electrostatic clamps work in air but electrostatics must be designed to reduce the effects of moisture conductivity in air.
- Liquid water should be kept out of the electrostatic electrode area with a good edge seal.

Can electrostatic chucks grip insulating substrates such as glasses, fabrics?

- Yes but the chuck design is different and the grip method is different; bulk dipole polarisation.
- Grip pressures are typically about half of what can be attained with conductive substrates.

Does the electrostatic field appear at the substrate surface?

- Conductive substrates gripped by a bipolar chuck attain a surface potential balanced in between the two electrode voltages; for identical electrode conditions, the substrate surface voltage is exactly half way in between the two electrode voltages.
- Insulating substrates permit penetration of the electrode dipole fields through to their top surfaces. The substrate thickness and dielectric constant control this field penetration.

Thermal and Rf Transfer Efficiency

Is backside gas required?

Thermal transfer between chuck and substrate in vacuum is through radiation, or various forms of enhanced direct contact. Enhanced contact between substrate and chuck improves upon the point contacts obtained with light contact pressures, and yields more heat transfer than radiation at all silicon plasma processing temperatures.

Solid contact yields excellent heat transfer, but deposits particles on the substrate rear and may result in high residual sticking forces.

Conforming contact is obtained with materials like silicone as the chuck dielectric.

Crushing contact yields contact regions of deformed material which enlarge with grip force. [These grip forces are obtained with conducting Johnsen-Rahbek chucks] Electrostatic clamping on a non-conforming chuck thus yields a radiative plus a crushing contact heat transfer contribution.

Gas contact typically increases on direct contact heat transfer by a factor of 2 - 4. It permits simpler substrate release and deposits fewer particles than high levels of solid contact. Gas is now the most popular heat transfer medium.

Thermal conductivity κ_{th} is typically 300 / 500 W m^{-2} K^{-1} at 10 /20 Torr He backpressure for Coulombic chucks. Divide the true discharge power density at the chuck surface by this number to obtain the temperature (°C) rise from chuck surface to substrate.

Electrostatic Chucks gripping Small Die on a Mobile ESC Carrier Wafer

The region around irregular substrates requires masking from the discharge, beam, etc. Monopolar chucks can tolerate any shape; bipolar chucks should have equal area under substrate, or grip potentials balanced, to minimise substrate voltage. If require cooling using gas contact, inject in a region smaller than any expected fragment. Cooling will degrade outside this region roughly linearly to the outer edge. For more details see http://electrogrip.com/EgripWeb2018/EgripProducts/systems/EgripMESC.htm.

Rf voltage limits in the chuck

Current density Estimate from bias voltage and true discharge power input: since

$$P = V_{rf}\,(\mathrm{rms})\, I_{rf}$$

$\approx 0.7\, V_b\, j_{rf}\, A$, where

P is the (true) discharge input power in Watts,
V_b the bias voltage, assumed to be $V_{p-p}/2$ where
V_{p-p} is the peak-to-peak rf voltage,
j_{rf} the target current density, and
A the target area;

Thus $j_{rf} \approx P / [\, 0.7\, V_b\, A\,]$.

So low bias voltages for a given power yield higher current; in, for example, ICP reactors.

Rf voltage drop in the dielectric layer

$V_d = j_{rf}\, d / [\, 2\pi f\, \varepsilon_0\, \kappa_r\,]$ where

V_d is the chuck dielectric layer voltage drop; and
f the rf frequency. Other terms are as in the first section.

The rf voltage, current, and power limits

Rf voltage: The maximum rf voltage is determined by plasma bias voltage limits in the chuck base, rf filters, and in the electrostatic driver output isolation. Electrogrip's DR5VI and DR6VI standard isolation voltages are 4kV, implying an rf maximum of 8kV$_{p-p}$ in asymmetric rf diode systems. The legacy system rf filters for DR4 and GC3 operation (RFF1 for motor drive, and BD3 for electrostatic drive) have a 2kV limit, i.e., 4kV$_{p-p}$.

The DR5, DR6, and DR7 systems perrmit a virtually unlimited rf or high dc voltage to be applied since they employ power couplers; for more details see http://electrogrip.com/EgripWeb2018/EgripProducts/electronics/EgripPowerCouplers.htm.

Rf current: The maximum rf current is determined by backside gas discharges and dielectric heating of chuck components. Electrogrip internal tests have demonstrated >400 A/m^2 rf 13.56MHz current flow without He arcing, and ~10,000 A/m^2 rf 13.56MHz component overheating limit.

Rf power: There are three limits to *true discharge* chuck power (excluding losses):

electrical the maximum [rf voltage] . [rf current] product;

chuck thermal the maximum chuck layer temperatures, their thermal conductivities, and the minimum coolant temperature determine the heat transfer capability;

substrate thermal the maximum substrate temperature T_{smax}, the gas gap thermal conductivity κ_{thg}, and the minimum chuck surface temperature T_{cmin} yield the substrate thermal limit, $P_{max} = \kappa_{thg} A\, [\, T_{smax} - T_{cmin}\,]$.

Gripping, Releasing, and Moving Substrates

Holding and sensing GaAs and glass

Gripping: Both good and poor conductors (such as Si and semi-insulating GaAs) are electrostatically clamped by a "parallel plate" attraction mechanism and yield identical clamp pressures. However, more perfect insulators (e.g., glass) require a "dipole" attraction mechanism and require interdigitated chuck electrodes, yielding lower clamp pressures.

Position sensing: Substrate sensing measures the capacitance of a substrate on the chuck, using charge transfer rates higher than for gripping operations. Thus semi-insulating GaAs and glass can exhibit smaller sense signals than those for Si or doped GaAs. Systems which must accommodate widely varying substrate types must therefore switch sensing modes. Such switching is a standard feature of Electrogrip drivers.

Effects of oxide on wafer; insulating films on substrates

Thickness effects: In chucks using *capacitive* (Coulombic) parallel-plate electrostatic attraction, insulating film thickness adds to the total dielectric thickness in the chuck and decreases forces. Such effects become smaller with increasing chuck dielectric thickness.

Example: an anodised Al or ceramic chuck dielectric with $d = 50\mu m$, $\varepsilon_r = 9$. Addition of 2µm of $\varepsilon_r = 4$ oxide dielectric decreases grip force by about 10% (see earlier formulas).

Conduction effects: If the chuck uses *conductive* (J-R) "dielectric" layers, the requisite current flow will be blocked by a dielectric substrate coating. Proper grip forces would be in this case retained through dielectric conduction / Fowler-Nordheim tunnelling current through the substrate dielectric at numerous conduction spots on the underside. Electrode voltages must be high enough to cause this partial electrical breakdown. This is the major cause of grip force variation with substrate type. Electrogrip Coulombic-style chucks permit ~100µm oxide thickness, and do not require breakdown conduction, hence do not exhibit large variations in performance with substrate type changes.

Holding rough or bowed surfaces

...can the substrate bend to reduce gaps, for low gas leakage?

Chuck dielectric*:* Grip forces fall dramatically when the chuck-substrate gap becomes about as large as the chuck dielectric thickness. Hence 50µm alumina film chucks will pull in wafer bows of 10µm, but will have trouble with 100µm bow or gap sizes. A 500µm film chuck will pull in wafer bows of 100µm, but will have trouble with 1mm bow or gap size.

Substrate thickness: Deflection of a substrate with a given pressure is proportional to $(\text{thickness})^{-3}$. Hence thin-film magnetic head or stiff sapphire substrates with a given degree of bow require higher grip forces and thicker chuck dielectrics than silicon wafers.

Substrate diameter: Deflection of a substrate with a given pressure is proportional to $(\text{diameter})^{4}$. So larger wafers with a simple bow are easier to flatten than wafers with a 'potato chip' cross section exhibiting more than one bending mode.

What current/voltage is on wafer? (*Relates to damage, E-Beam field distortion*)

Average voltage: Imbalance in gripping electrode areas, voltages or chuck surface electrical resistance cause substrate voltage imbalance, and may result in device damage if the substrate is contacted to a different potential (via an electrode or a plasma). With a high quality chuck dielectric, dynamic balance processes such as provided with the Electrogrip drivers can yield residual voltages of less than 2.5V. In charged particle exposure (ion, electron beam) systems the substrate surface is grounded, further suppressing residual voltages.

Substrate current*:* Flows steadily through conductive (Johnsen-Rahbek) dielectrics, and in pulses through partially broken-down dielectrics such as aged anodised Al. Add the capacitive dielectric current $I_{cap} = C\,(dV/dt)$: C = interelectrode capacitance *through* substrate; while dV/dt = voltage rate of change has many possible sources: from grip and release, supply ripple, substrate movement, and sensing signals.

Current direction: Vertical (between substrate top and bottom faces) in monopolar chucks, lateral (across the rear surface) in other chucks.

Lateral voltage*:* Lateral current results in lateral substrate voltages, and for typical Si wafer resistivities and chuck geometries this current and voltage appear not only on the wafer rear, but radiating out through the Si wafer thickness, to larger thicknesses with lower substrate conductivities unless the current source and sink points are widely separated. This lateral voltage may cause device damage and deflect charged particle beams. Between widely-spaced current injection and sink points, the surface voltage per meter $E = [I\,\rho] / [t\,w]$, where I = current flow, ρ = wafer resistivity, t = wafer thickness and w = width of the injection electrode pattern. For capacitive current flows, $w \approx$ wafer diameter for a "double D" electrode pattern, and w ≈ 2x[wafer diameter] for a "ring and circle" electrode pattern. By limiting the rate of voltage change on the electrodes, as is done in the Electrogrip DR4 driver, such lateral voltages are held to millivolt levels between any two points on wafer surfaces and through their bulk for typical wafer backside resistivities.

Example #1: For wafer resistivity r = 10Ω-cm [= 0.1Ω-m], thickness t = 0.5mm, and diameter d = 200mm, $E = 10^3$ I. To damage devices with 1cm antenna structures and 10V damage threshold, E = 1kV/m, requiring I = 1A. Such a high current is not normally available from electrostatic power supplies. However if there is arcing from chuck to wafer, either from catastrophic or randomly periodic partial breakdown events (eg, anodised Al dielectrics), there is little to limit current flow from the capacitive stored charge in the electrostatic electrodes. In the latter case, arc current or wafer surface voltage levels should be tested to assure low device damage. Coulombic Electrogrip chucks do not normally arc, and exhibit steady state leakage currents <<1μA.

Example #2: Total current flow during grip and release using the DR4 driver is proportional to grip potential and chuck area. For 200mm chucks with ±4kV electrode potential, the peak current flow is 40μA between the electrodes. For 76mm (3") chucks using ±4kV the peak current flow is 6μA. These currents can be reduced, if desired, by increasing the DR4 driver ramp timing parameters. Substrates with uniform conductivity through their bulk will spread this current throughout; those with highly conductive surface layers such as doped epitaxial films on semi-insulating substrates will concentrate this current in the surface layer.

<u>Attaining Reliable Release:</u>

No dielectric layer is perfect so conduction, charge trapping, and migration of charges on surfaces will occur with even the best electrostatic chucks. In addition the exposed surfaces of both chuck and substrate offer more opportunities for charge movement than in a fixed capacitor construction. Electrogrip has developed adaptive charge cancellation methods in its DR high voltage driver series which reduce the memory effects resulting from undesired charge movements, enabling reliable grip and release.

Please refer to Electrogrip's 'Grip and Release', 'Charge Control', and 'Chuck Leakage' tutorials for more information.

Power supply choices

<u>General</u>: High voltage, low current output is required. For monitoring power supply operation, chuck end-of-life detection, and in some chucks for grip confirmation detection, voltage and current monitoring is required. Power supplies for rf chucks must float with rf bias. Such floating power can be rf-decoupled with filters as in the DR4/BD3 system, or isolated, as in the DR5VI and DR6VI systems.

Monopolar chucks require that the voltage between substrate and chuck electrode (which may be the insulated chuck body) be held constant. Grip requires plasma or other contact to the wafer. Plasma contact to the substrate requires that the electrostatic power supply track the plasma bias potential.

Bipolar chucks are referenced to the wafer / plasma bias potential, thus the two grip electrodes require a symmetric bipolar power supply floating at the bias potential.

Tripolar chucks are driven similarly to bipolar chucks. However the tripolar base electrode can often be used as a reference electrode. The Electrogrip DR4, DR5, and DR6 drivers contain two independent bipolar high voltage power supplies which ride on the rf plasma bias potential. These two power supplies drive each electrostatic grip electrode with balanced voltages of whatever polarity is required to obtain the best grip and release. Thus the DR4, DR5, DR6 and DR7 systems can drive bipolar and tripolar chucks; and the DR5, DR6 and DR7 can also drive monopolar chucks since their substrate sensing works with monopolar electrodes. These supplies also have self-learning and user-adjustable features which can adapt to gripping highly resistive substrates without device damage, and which assure reliable grip and release on any substrate type.

Multi-Pole chucks with (say) 6 electrodes may require 3-phase ac drive. Electrogrip provides its DR5V, DR6V and DR7V power supplies with a DRxP add-on 4-output module yielding a compact solution with 6 high-speed independent bipolar high voltage channels of up to ±6kV.

Internal or external lift pins?

Electrogrip can provide chucks which interface with external pins, or with an internal lift mechanism. External pins may be in notches around the chuck OD, while internal pins may be at the gas distribution area near the chuck OD, and often smaller in diameter since are internally protected. Internal pins are at rf potential so require air-side isolation. External pins pick up some of the required rf potential so must be insulated in vacuum.

EXTERNAL / INTERNAL WAFER LIFT PROPERTIES

TYPE OF WAFER LIFT; PROPERTY	**External**	**Internal**
Rf, thermal uniformity	worse	better
Lateral retention	lift pins may retain substrate	not possible; use chuck rim
Lifter vibration	pin rubbing	pin guide rubbing
Lift pin discharges	hollow cathode (under wafer)	He arc (at highest rf currents)
Lift pin adjustment	simple access	more difficult access
Lift mechanism atmosphere	process gas	He backfill gas

Gripper "Pole" Number Choices and Wafer Contact

CHUCK POLE NUMBER CHOICES

POLE NO.: PROPERTY	**Monopolar**	**Bipolar**	**Interdigitated**	**Tripolar**	**Multipolar, ac**
Rf uniformity	Excellent	Best if couple to both poles	May require rear tripolar plate	Excellent	Couple to poles or rear plate
Grip force	High	High	Med	High	Med
Substrate sense	DR5/DR6	DR4,5,6	DR4,5,6	DR4,5,6	DR5
Electric contact to Substrate?	Required	No	No	No	No
Plasma contact to grip electrode?	Design - dependent	Yes	Design - dependent	No	Design - dependent
Can it hold dielectrics?	No	No	Yes	No	No
Fast release possible?	No	Yes	Yes	Yes	Yes
Substrate vibration?	Low	Low	Low	Low	High
Single cooled	Yes	Not normally	Yes with rear rf tripolar plate	Yes	Yes with rear tripolar plate
Complexity	Low	Medium	High	High	Highest

Material Choices; What causes failure?

3 lifetimes: Electrostatic chucks are limited by three basic lifetimes; electric, chemical, and mechanical. The shortest dominates chuck life.
Mechanical; The chuck surface must withstand the scrubbing effect of wafers, crushing of occasional particles on the surface, and cleaning.
Electrical; Plasma "accidents" occur due to broken wafers, He backside arcs, and overpressure-popped wafers. In addition arcs of one electrode to the baseplate cause the opposing electrode to reach double the applied voltage. All such arcs can destroy dielectrics with low electrical strength.
Chemical; Etch and cleaning processes result in chuck edge/surface attack. Plasma cleaning may also expose the entire chuck surface. Yttria/Alumina ceramics / sapphire are the most plasma-resistant surfaces; organic plastics the least resistant.

Electrogrip chucks routinely process millions of substrates before refurbishment. When refurbishment is required, Electrogrip's vertically integrated coating, and cleanroom test and packaging ensure rapid turnaround.

Which dielectric type? / temperature limits
Two principles: Two major electrostatic gripping principles are in use today. Both rely on the attraction of opposite charges. One method is an "*ideal*" attraction of two parallel plates of charge, with no current flow between them. The other is "*Johnsen-Rahbek*" attraction of surfaces which have current flowing in randomly spaced contact spots between them. Ceramic chuck data shows J-R attraction high between 10^{13} and 10^{8} Ω-m.
Timing: All dielectrics leak some current, so all chuck materials approach Johnsen-Rahbek conditions given enough grip time to allow charges to move in the dielectric and arrive at a stable configuration. For good dielectrics like quartz or sapphire at room temperature, such times are many hours to days; other materials exhibit time scales of minutes to seconds.
Temperature: All materials become J-R types at temperatures high enough to bring dielectric resistivity into the J-R regime. Temperatures are limited by dielectric conduction.
Overall: Insulating chucks are tolerant of insulating substrate coatings, and yield low backside particle counts, long grip time, and wide temperature range. In other respects J-R chucks will often yield better performance.

INSULATING vs. JOHNSEN-RAHBEK DIELECTRICS

TYPE: PROPERTY	Insulating	Johnsen-Rahbek
Grip force	Medium	High
Uniformity of grip force	High	Varies
Thermal conduction		
no gas	Low	Medium
with gas	Medium-High	High
Rf current tolerance	Good	Varies
Backside particles	Low	High
Substrate current flow	No	Yes
Wide temperature range	Yes	No
Grip force vs. time	Steady	Varies

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