Electrophorectic Self Assembly, A Manufacturing Process for Various Industries

Robert H. Detig
Pres. & Founder, Electrox Corp.
Denville, New Jersey, USA

Abstract

Electrophoretic Self Assembly (ESA) is the name for a manufacturing process where large, functional particles (hundreds of microns) are imaged or properly placed using the electrical forces found in the electrophotographic imaging process. The functional particles are the "toners", in this case liquid toners; and the imaging surface is a fixed configuration printing plate or the traditional optically addressable plate.

A typical use for this technology is the high volume manufacture of RFID(radio frequency identification tags). Silicon die of the order 400x400x50 micron in dimension needs to be accurately placed in X & Y; rotated in alignment with the x axis, and oriented (heads vs tails) or correct side up. For commercial success this needs to be done quickly and at cost levels approaching the graphic art industry. I will describe experiments in which silicon die is coated (one side) with a charge control layer, which when dispersed in an Isopar diluent (containing a suitable charge director); will impart are suitable ionic charge to the die. This will allow it to be placed, rotated and oriented on a suitable substrate.

The presentation will report progress in this endeavors and include calculations of the expected imaging forces and a limit to the largest die than can be imaged. Other possible commercial applications will be discussed.

Introduction

With the desire to produce large display devices (1/4 x 1/2 meter) at low cost with distributed active circuitry, and with the need for high performance circuits (mobilities of 500 to 1000 $cm^2/v\cdot sec$) engineers have looked for ways to place small active components over relatively large areas at very low cost. Sputtered amorphous Si and printable organic semiconductor materials have very low mobilities (approximately 1.0) so single crystal Si is the only option.

Work done at the University of California evolved into the Fluidic Self Assembly Process.[1] The company Alien Technology of California is commercializing this. In this process Si die are etched into truncated pyramids whose top is sliced away. These die are dispersed in an aqueous medium and flowed over an embossed surface with a mating pattern of truncated pyramidal depression in its surface. Alien has raised a significant amount of capital investment and is in the process of commercialization.

M.B. Cohn describes another approach.[2] In this process a pair of oppositely charged planar electrodes are vibrated, with apertures in the upper electrode though which parts are attracted by the electrical fields. To quote the abstract "The method relies on vibration and weak electrical and magnetic forces." By weak they mean that the particles are uncharged but because they conductive are have a significant "dielectrophoretic" force.[3] For decades it has been understood the forces from "dielectrophoresis" are about 10% of the Lorentz force (qE)! More results on this activity are shown in Ref. 3.

In another approach to imaging "components", work from Nanogen, Inc. of San Diego, California is significant.[4] This technology uses techniques of the DNA electrophoresis in aqueous systems. One quote highlights the thrust of this patent "specific DNA polymer sequences may be covalently bonded…to LED devices and complementary sequences to motherboard materials…" This approach is worth following, especially for the micron and smaller structures or parts to be imaged.

Making a Silicon Die Toner

Mainstream silicon production is on 200mm diameter wafers with 300mm being the leading edge fabrication. Let us deal with 200mm wafers; they are routinely "thinned" by mechanical grinding or plasma etching to 125 micron thickness, with the next objective to be 75 or 50 micron (mainly for the smart card industry). Figure 1 shows the silicon die modified to make it function as a toner particle. A typical silicon integrated circuit chips consists of a single crystal silicon substrate, one side of which is highly polished. On this surface various layers of p&n type material are grown from the vapor phase with layers of SiO2 dielectric and metal (aluminum and copper) to interconnect the various parts. This functional circuitry occupies a depth of one or two microns. On top of these parts are deposited the Input/Output (I/O) pads which connect to the outside world. Between the pads is the passivation layer that protects the active circuitry from contamination from the outside. This material is typically silicon nitride.

Over this is added a photo definable resin layer to serve as the charge control layer. This is typically a resin layer with strong acidic or basic functionality. When the coated die are dispersed in an Isopar diluent containing a suitable charge director; acid/base reactions occur between the charge control layer and the charge director material yielding a definable "ionic" charge on the die. It therefore can be directed, moved, imaged, etc. with an electrostatic field.

To better illustrate, if the charge control layer has acidic functionality, a hydrogen ion from the surface of the charge control layer is "ionized" into the Isopar diluent where it is surrounded by charge director molecules thereby forming an inverse "mye" cell with a positive charge, leaving the charge control layer (and necessarily the chip) with a negative charge. Materials with strong hydroxyl functionality lose a hydroxyl ion yielding a functional particle or chip with a positive charge. Some interesting resins and charge director materials are discussed by Swidler.

Figure 2 shows the charge configuration on the die toner particle. This shows a die 50μ thick with a 5μ thick charge control layer. Since the silicon bulk is substantially conductive, typically 1 to 500 ohm·cm; the mobile carriers in the chip, form a positive charge layer under the active circuitry, thereby forming a closely coupled dipole and equal and opposite charge (negative) on the other side of the chip. Note, even a substrate made of soda lime glass (window glass) with a charge decay time constant of a few seconds would quickly adjust to the above charge configuration. With this one sided charge configuration, one conceivably has the ability to orient the die correct side up or correct side down. Note Figure 1 shows the charge control layer on the top (active component side) of the chip, but it could optionally be put on the opposite side of the wafer at no additional cost.

The Role of the Charge Director

In the approximate forty years of liquid toners, various types of charge directors have been used. They can be broadly grouped into two categories:

a) Those that attached themselves to the toner particle
b) Those that remain with the diluent liquid (the Isopar)

The first group will attach itself to all surfaces of the particle, thereby negating the ability to preferentially orient (heads vs. tails) the particle. On the other hand, if you want to image functional particles without a first resin coat (no charge control layers); these charge directors are very useful. But if you want the single side charge configuration, the second group are the ones needed for this process. Swidler describes charge directors that readily attach to toner particles.

Early Examples of Large Particle Imaging

The first automatic office copier was the Xerox 914 introduced in 1959. It used a dry toner developer in which 10 to 12 toner particles attached to 650 micron coated "sand" were poured over the image drum. There was no "closed loop" control over toner concentration, so if low concentration dropped too low, Q/m of the toner rose; as did the Q/m of the carrier particle. Then the carrier particles would image the drum in the periphery of the image (the wrong sign region) and be carried out on the paper and would cause "tenting" of the paper during the transfer or damage the drum. This was the origin of the term "bead carry out" within the dry developer community. To increase image speed, more developer mass flow was required so bead size shrunk to 400, then 250 micron glass spheres making the problem worse. In all cases the gravitational force (m·g) competed with the image force (q·**E**).

The next step was to transition to higher density carrier particles, nickel and iron. Finally there was the transition (within Xerox at least) to the magnetic brush developer in the X-3100 in 1972, 7400 in 1976. That same year Siemens introduced their ND-2 high-speed laser printer at about 200 pages per min. All these machines used magnetic brushes with coated 100 micron iron carrier for the X-3100 and 100 micron uncoated iron for the Siemens ND-2. Despite the more powerful magnetic fields holding the iron particles to the brush, "bead carry out," (imaging of the carrier particle) continued to occur. In cascade systems, only gravity was preventing the carrier particles from "imaging". Table I shows the relative mass of various toner particles with the mass of a 10 micron dry toner particle as a bench mark (IX); various other particles of interest, including solder particles of 20 and 100 micron in diameter and silicon die of 400 x 400x50 micron, and 1 mm^{2}x50 micron (a large RFID chip).

Table 1

Material	Size (microns)	Density	Mass ratio	Mass (10^{-6}gm)
Resin	1μ	1.0	.001x	
Resin	5μ	1.0	.125x	
Resin	10μ	1.0	1x	
Metal (Sn/Pb)	20μ	8.5	68x	
Metal (Sn/Pb)	100μ	8.5	8500x	4.41
Metal (Fe)	100μ	7.9	7650x	3.96
Silicon	400μ x 400μ x 400μ	3.2	≈100Kx	51.2
Silicon	610μ x 1650μ	3.2	≈600Kx	322

Notice the 100 micron iron carrier particle is about 8,000 times more massive than the 10 micron resin particle that it carries on its surface.

The Electrostatic Force on Si Die Toner Particle

Some typical RFID chips are:

Texas Instruments	2.25mm x 1.5mm
Micro Chip Int	1.5mm x 1.4mm
Hitachi	400μ x 400 μ
Alien Tech	325 μ x 325 μ
Electrox Test I	200μ x 800 μ
Electrox Test II	610 μ x 1.65mm (1mm^2 area)

If we choose as our benchmark for large particle image as the 100 micron dia. Iron carrier bead of the X-3100 or Siemens ND-2, then the Hitachi chip thinned to 100 microns would be 12 times the mass of the iron carrier particle. A much larger RFID chip, the Electrox Test II at one square mm in area (610 µ x 1.65mm) is 77 times more massive than the 100 micron iron carrier particle. One might question "Are the electrostatic forces sufficient to image such a massive particle?" The answer can be found in an estimation of available electrographic experience.

Large scale black/white digital printers like the Xerox Docutek or the Siemens/Oce Page stream printers print 10 micron die resin toner that has a typical charge per unit mass.

$$Q/m = 20 \text{ mico coulomb/gm} \tag{1}$$

$$\text{particle dia} = 10 \text{ micron} \tag{2}$$

$$\text{particle density} = 1gm/cm^3 \tag{3}$$

From this data, one can calculate the surface charge density (D coul/m^2) of charges on that toner particle. Doing the appropriate algebra we find

$$Q/A = 100/3 \times 10^{-6} \text{ coul}/m^2 \tag{4}$$

Now, let us determine when the electrostatic force equals the gravitational force

$$\text{Electrostatic force} = Q/A \cdot \text{Area} \cdot E \tag{5}$$

$$\text{Gravitational force} = m \cdot g \tag{6}$$

$$\rho \cdot \text{Area} \cdot \text{thickness} \cdot g \tag{7}$$

where E, the development field, V/micron
P, density of Si, 3.2 gm/cm^3
g, the gravitational constant
Area is the effective area of the charge control layer, one side only.

Notice, in an RFID chip with only a few I/O pins, sometime two the effective area of the charge control layer approximates that of the actual area of the silicon.

If we ask "When does the electrostatic force equal the gravitational force?"; the area terms cancel out yielding; one variable t, the thickness, as the quotient of four constants.

$$t = Q/A \cdot E \cdot 1/g \cdot 1/\rho \tag{8}$$

where,

$$Q/A = 100/3x10^{-6} coul/m^2 \tag{9}$$

$$g = 9.8m/sec^2 \tag{10}$$

$$\rho = \text{density of Si} = 2.33gm/cm^3 \tag{11}$$

$$E = \text{development field} = 1volt/micron \tag{12}$$

$$t = 1.46x10^{-3}m \tag{13}$$

Therefore a die 1mm thick would have an electrostatic force of 1.46 g's; a 100µ thick die, a force of 14.6 g's; a 50 µ die, a force of 29g's.

This is indeed very encouraging. If Alien Technology can place die using gravity alone (1g!), then we in the electrographic community have much higher force levels available to us. In addition, our external electrical field can be time modulated, focused, stepped, ramped etc. using a relatively inexpensive power supply.

A similar calculation for the size of an iron particle whose gravitational force equals the electrostatic force yields.

$$r = 3D \cdot E \cdot 1/\rho \cdot 1/g = 1.299mm \tag{14}$$

The Forces on the Silicon Die Toner Particle

The forces of the Si die toner particle in the liquid dielectric dilouent material;

Force of gravity
Viscous forces
The dielectrophoretic force
The Lorentz force

The last force comes from the free charge on the particle (the electrochemical charge) and the electric field.

$$F_l = q \cdot \mathbf{E} \tag{15}$$

The dielectrophoretic force is;

$$F_{diel} \text{ is proportional to (dielectric constant)} \cdot \text{grad } \mathbf{E} \tag{16}$$

It is an analog to the force holding an iron or ferrite particle in a magnetic brush. With resin toners of dielectric constant between 3 and 3.5, the F diel is usually one-tenth the Lorentz force. With electrically conducting particles (like a silicon die with resistivity of between 5 and 50 ohm·cm), the effective dielectric constant is very high so the dielectrophoretic force can be substantial. We will show photos of uncoated die 200 u X 800 u X 50 u thick that were very nicely placed and oriented by dielectrophoretic forces. Un fortunately the dielectrophoretic force is independent of the polarity of the charge producing the electric field of increasing strength.

The Task of Properly Placing a Silicon Die Toner Particle

The goal is to place a die toner particle in X & Y (location), aligning it with the electrode pads of the RFID antenna substrate (rotation); and orienting properly so the electrode pads on the chip mate with the electrodes on the substrate (orientation). Or to summarize:

Location	X & Y
Rotation	Theta
Orientation	Obverse vs. reverse side (heads vs. tails)

A. Location

RFID substrates could be as small as 50mm long by 6.33mm high on a 50 to 75 micron thick film of PET. With these dimensions 8 tags fit within a 50mm by 50mm area of film. A machine printing a 0.5 M wide web at a process speed of 0.25 M/sec would produce 1.44 Mil tags per hour or 2.99 billion tags per year (one 8 hour shift). We therefore want to place one chip every 50 mm across the web and every 6.33 mm along the web.

B. Rotation

If you make the chip long and thin with an aspect ratio of 3 or 4 to 1, the chips will tend to align themselves on a line of charge. We will show samples of chips imaged by dielectrophoretic forces that substantially align themselves along a line of charge. These die are 200 μ by 800 μ (the equivalent area of the Hitachi chip).

C. Orientation

While it is possible to manufacture die with electrodes on both sides of the die, one pays a considerable price to achieve this in terms of more silicon "real estate" consumed on the chip. A rough estimate is that for a 50 μ thick chip, one needs a piece of "real estate" of 100 μ by 100 μ devoted to the I/O pads alone. For a two terminal part (with redundancy- four terminals total), this means that 200 μ by 200 μ are needed for the I/O pads alone. This is 25% of the area of the Hitachi chip or a 20% increase in the cost of the chip. It has been reported that Alien Tech. has a double sided RFID chip.[5] Those interested in double sided silicon can contact Tru-Si Technology of Sunnyvale, Cal.[6]

In RFID cost considerations are paramount so the orientation of a single sided chip is a major goal of a successful placement technology. One technique to orient a chip with a single sided dielectric coating is to re-do a very early experiment in electrostatics.[7] Conductive particles between two conductive parallel planes will jump back and forth under sufficient electric field, in either air or a dielectric liquid. If the particles are coated on one face with a dielectric material, and they land on the top plate with coated side against said plate; they will not re-charge with the opposite polarity. The retained free charge that drew it to the plate will hold them tightly to the plate. We will show an example from such an experiment that produced proper orientation of a single side coated particle.

Results

We will present an update on the experimental progress to date in the electrostatic placement of silicon die toner particles (surrogate RFID chips) both 200 u by 800 u and 610 u by 1.65 mm (1 sq. mm of area), in various chip thicknesses.

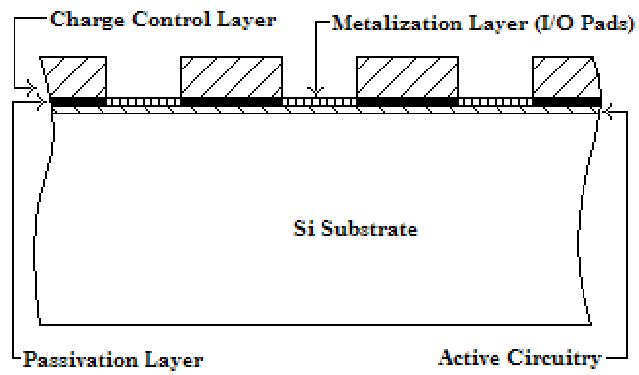

Figure 1. Si Chip Showing Charge Control Layer.

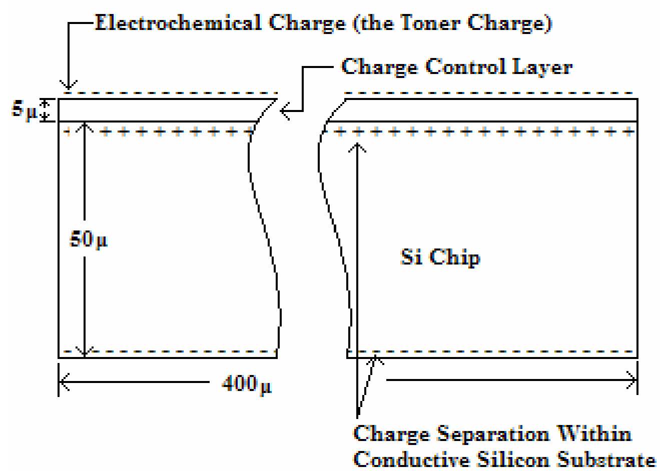

Figure 2. The Charge Configuration of a Si die Toner Particle.

Conclusion

Very large electrostatic forces (10 to 20g equivalent) can be achieved on commercially interesting silicon part sizes (in the area of 1 sq. mm), and some of the orientation and alignment tasks have been demonstrated. Electrophoretic Self Assembly or the placement of useful parts in a very inexpensive process could, someday, be an important industrial process.

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Biography

Robert H. Detig founded Electrox Corporation in 1992 to apply electrographic imaging to technology as a manufacturing tool for various industries. He has some of the basic patents relating to the polymeric electrostatic printing plate. He has extensive experience in all aspects of the electrographic imaging process going back to his early years at Xerox. He has pioneered the concept of functional toners made of high density materials like metals and glasses; to be used in a manufacturing process.

He was awarded a PhD in Electrical Engineering from Carnegie Mellon University in Pittsburgh, Pennsylvania