Combinatorial Particle Patterning

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The unique properties of solid particles make them a promising element of micro- and nanostructure technologies. Solid particles can be used as building blocks for micro and nanostructures, carriers of monomers, or catalysts. The possibility of patterning different kinds of particles on the same substrate opens the pathway for novel combinatorial designs and novel technologies. One of the examples of such technologies is the synthesis of peptide arrays with amino acid particles. This review examines the known methods of combinatorial particle patterning via static electrical and magnetic fields, laser radiation, patterning by synthesis, and particle patterning via chemically modified or microstructured surfaces.

1. Introduction

The term "combinatorial patterning" describes the possibility of generating different particle patterns on the same substrate. One of the most common methods of the combinatorial patterning of particles is laser printing. Invented by Chester Carlson, today, the xerographic method is present in practically every office in the form of laser printers.[1] The development of the printing technology has driven many technological and scientific breakthroughs. In the past decades, particle technology has experienced huge progress. Compared to fluid droplets, solid particles keep their shape, even at the nanometer scale, they do not spread or evaporate during deposition, and they do not dissolve previously deposited material. Furthermore, solid particles can be used as vehicles to transfer chemical substances to spatially defined synthesis areas. Chemical compounds embedded within the particles are protected against decay. One example for the patterning of "smart particles" are particle arrays, where they support the oligonucleotide sequencing or the peptide synthesis with amino acid particles.[2,3] The manipulation of "smart particles," which embed different types of molecules, combined with the screening in the high density array format, promises the development of novel assays and materials.

Although various methods of particle manipulation are already known, less attention was paid to their application to combinatorial particle patterning. Thus, in this review, we discuss current methods of combinatorial generation of micro and nanoparticle patterns, focusing on the possibility of generating different particle patterns on the same substrate. Furthermore, we demonstrate a novel method for particle pattering in microstructures.

As an overview, **Table 1** summarizes the different technologies we discuss and their applicability and technological maturity for combinatorial particle patterning.

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2. Electrical Particle Patterning

2.1. Ionography

Patterning of electrical fields, often referred to as the generation of a latent image, is a widespread method for particle patterning. Electrostatic forces, generated by spatially defined charge patterns, can attract particles to a substrate, used in, e.g., ionography, nanoxerography, or chip-based methods. Furthermore, we consider the generation of particle patterns in laser printing (electrophotography).

In ionography, the driving force of particle pattern formation is the Coulomb force. First, a latent electrostatic image is created, but, instead of using a photosensitive material, ions are directly deposited on an insulating dielectric surface (**Figure 1**a).[4] Afterward, the image is developed by self-assembly of charged particles, either from suspension or from aerosol.[5,6] Specifically charged particles are attracted to the oppositely charged areas and repelled from equally charged regions of the electrostatic image. For example, a Ga^{+}-focused ion beam can be used to positively charge the irradiated areas of a $CaTiO_3$ substrate.[5] Negatively charged microparticles from a suspension are then attracted to these areas. Also negatively charged regions can be created, for instance, by using an electron beam.[7]

Arbitrary patterns can be easily generated by changing the drawing pattern of the focused ion beam.[8] The results of such pattern deposition, observed with a scanning electron microscope (SEM), reveal that several contaminating particles are visible, i.e., particles are deposited on places which were supposed to have a repelling effect on the particles (Figure 1b). In addition, the deposition of individual 10 µm polymer particles with 50 µm spacing was reported; in this case, the diameter of the particle was exceeding the electrified area.[5] A possible limitation of the spacing results from the spreading of the electrified region by diffusion and conduction of charges in the substrate. An ion beam diameter of 0.2 µm results in charged spots, which are about 25 times larger than the beam diameter.[8]

Charged particles can also be deposited on a substrate with electrostatic lenses. These are formed through ions of the same charge.[6] It is, however, necessary to create a photoresist pattern first. N_2^+ ions accumulate on the resist but are neutralized where there is no resist and, therefore, create a charge pattern. Positively charged particles from an aerosol are repelled by the ions and only settle on areas without photoresist. Afterward, the resist is removed and the particle pattern remains. Different regularly shaped patterns have been reported, the generation of arbitrary patterns is not possible, since the focusing effect does not apply to irregular shapes.[6] As soon as the ion concentration is too low, the surrounding area is contaminated. Due to the focusing effect, the generated particle patterns are much smaller than the photoresist patterns.[6] A 230-nm-wide gap in the photoresist did create an only 75 nm wide line of 10 nm silver particles with a line spacing of about 770 nm. A combinatorial deposition of particles has not been reported yet.

2.2. Nanoxerography

Nanoxerography is the creation of an electrostatic latent image using a stamp.[9–12] A flexible, metal-coated poly(dimethylsiloxane) (PDMS) stamp is used to transfer electric charges onto a 80 nm thin PMMA (Poly(methyl methacrylate)) substrate, which is placed on top of a conductive support.[10] Other thin-film electrets have been reported as well. The stamp is brought into contact with the substrate and a voltage of 10–20 V is applied between the stamp and the conductive support.[9] During this printing process of about 10–20 s, a charge of 10–100 mC cm^{-2} is transferred.

To achieve an even higher resolution, a flexible thin- and fine-structured Si electrode can be used as a stamp.[12] PDMS is still used in this case, but only as a flexible support for the Si electrode.

Contact electrification is also possible between two dielectrics.[11] In this case, the PDMS has no metal coating but is cleaned and activated with oxygen plasma. Upon contact, the substrate is charged via hydrogen proton transfer, due to the difference in chemical potentials. For example, an SiO_2 substrate accepts protons and is thereby charged positively, whereas a deprotonated PMMA substrate donates protons and will carry negative charge after the printing process.[11] Again, the electrostatic image is subsequently developed with charged particles.

Arbitrary patterns should be possible. However, only regular dot, line, or ring patterns have been reported. The stamps can be reused several times, but for each pattern, a different stamp has to be produced in a complex lithographic process.[9,11]

For the electrostatic image, a resolution of as low as 100 nm was achieved, which was also the resolution of the Kelvin probe force microscope, used to detect the surface potential.[10,12] The developed pattern with 80 nm graphite particles allowed for a

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Frank Breitling did his habilitation in 2003 in high-throughput screenings at the University of Heidelberg, after studying biology and receiving a PhD. He developed the technology of recombinant antibodies at the Deutsches Krebsforschungszentrum (DKFZ). As a member of the DKFZ research group Molekulare Genomanalyse with Prof. Annemarie Poustka (1997–2004) and later within the independent research group Chipbasierte Peptidbibliotheken (2004–2009), he worked on particle-based, high-density peptide arrays. Since September 2009, he has been positioned at the Karlsruhe Institute of Technology (KIT).

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