Use of patterned magnetic films to retain and orient micro-components during fluidic assembly


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Patterned thin magnetic films have for the first time been used to orient and retain micron-sized III-V elements on silicon substrates during fluidic hybrid assembly. Modeling of the forces between Ni thin films patterned on one surface of 5–6 μm target areas on Si substrates predicts that the strength and fall-off characteristics of the attractive forces can be engineered to orient and securely retain only pills that are right side up. Verification of this behavior has been obtained by assembling 50×100 μm² micropills in recesses with patterns of Sm-Co rectangles. © 2009 American Institute of Physics. [DOI: 10.1063/1.3076146]

Historically, functions not available in a single silicon process or not even from silicon alone, as well as functions not easily fabricated in an integrated form, have been combined by hybrid integration of packaged components and, more recently, bare dies on printed circuit boards or multi-chip modules. As system performance increases, however, pressure grows to develop a technology that can be used to integrate disparate functionality on a single chip while reaping the traditional advantages in performance, packing density, reliability, and cost of monolithic integration. We have recently used such an all-inclusive monolithic integration technology that we call recess mounting with monolithic metallization (RM3) ¹ to integrate GaAs-based vertical cavity surface emitting lasers (VCSELs) within commercially processed integrated circuits (ICs) ². VCSELs fabricated in the form of 8 μm tall, 75 micron diameter pills were placed in recesses etched into the surface of an IC chip to expose buried contact pads, and were soldered in place. The surface was planarized with a spin-on dielectric, and the integration was completed by patterning thin film metal interconnects between contact vias formed on the chips and ICs.

An attractive candidate for automating such a microscale assembly of device pills in recesses is fluidic self-assembly (FSA) (Ref. 3); a process used successfully in industry to assemble full IC dies on plastic substrates. ³ However, FSA has not been as successful when applied to the micron-sized device pills in RM3 integration. The pills enter the recesses readily during FSA, but they also come out just as easily. They can also readily enter the recesses upside down unless additional processing is done to taper the sides of the pills and recesses. In this paper we show that magnetic thin films offer a solution to these problems and, specifically, that hard magnetic thin films suitably patterned in the bottom of recesses will retain pills with Ni on their underside that are right-side up but not those that are upside down and can also be used to orient and align pills to the underlying IC.

Magnetic fields have been used to assist macroscale assembly and alignment in both children’s toys and serious science. Focusing on the latter, Whitesides et al. at Harvard University used magnetic fields to self-fold planar shapes into three-dimensional (3D) structures and to self-combine three-dimensional units into complex assemblages. ⁶ Even more relevant to the proposed effort was the work of Lepselter et al.⁷ at Bell Laboratories and more recently with Shet et al.⁸ at the New Jersey Institute of Technology. Researchers working under Lepselter in the 1970s used magnetism to align beam leaded microchips with the leads on ceramic substrates. This unpublished work used magnetic forces to assemble and align much larger units than those of interest in the current proposal, but it directly supports our hypothesis that magnetic fields can be effectively used to assemble and align components. Shet et al.⁸ proposed using magnetic fields to do assembly by a relatively complicated technique that to our knowledge has not been put into practice.

In the present work we are concerned with assembling units on the order of 5–10 μm thick with lateral dimensions of a few tens of microns. The soft and hard magnetic films involved will ideally be only a fraction of a micron thick, and we are interested in the attractive forces at separations from as much as 20 μm down to zero.

The attractive force per unit area between a continuous thin film of Ni (in the x-y plane, thickness ts, and permeability μs) and an infinite periodic array of Sm-Co thin film rectangles (thickness ts and magnetization MR in the x direction) separated from it by a distance d can be calculated analytically. The result is dominated by the lowest order term in a Fourier series which is approximately

\[
F = \frac{4a^2 \mu_s M_R^2}{\pi^4} \left[ 1 - e^{-\frac{2\pi d}{a x_s}} \right] e^{-\frac{4\pi d}{a l_x}} + 2a^2 e^{-\frac{4\pi d}{L_x^2}} + 2a^2 e^{-\frac{4\pi d}{L_y^2}},
\]

where \(L_x\) and \(L_y\) are the periods in the x and y directions, respectively, the rectangles are \(L_x/2\) wide and \(L_y/2\) long, \(L_d = (L_x^2 + L_y^2)^{1/2}\) is the length of the diagonal of the rectangle,
and \( \alpha = L_z / L_d \). Significantly, the attraction decreases exponentially with increasing separation, \( d \), at rates set by the array periods, \( L_x \) and \( L_y \). Using this, one can tailor the extent of the attraction through the selection of the pattern period so that a pill Ni-side up in a recess is not retained because the separation between the Ni and Sm-Co films is too large, while a pill in a recess Ni-side down experiences an increasingly strong attraction as it falls into the recess.

We want the force retaining a pill fully in its recess to exceed the force of gravity on the pill (\( \approx 0.3 \) N/m² for a 6-μm thick GaAs layer) so it will not fall out when the recess is inverted. The first two terms in Eq. (1) are most important in determining this peak attractive force, i.e., the attractive force at small \( d \). Equation (1) teaches that there are two design variables, \( M_R \) and \( t_p \), available to ensure sufficient peak attractive force once \( L_z \) and \( L_y \) are chosen.

To model the geometries of finite extent encountered in practice, Maxwell 3D (Ref. 10) was used to model the force of attraction between single Sm-Co rectangles and a Ni thin film sheet and also between multiple Sm-Co rectangles and a Ni sheet.\(^{11}\) The results are consistent with intuition gained from the analyses of infinite films. For single rectangles the fall-off of the force with separation is faster for smaller rectangles, as Fig. 1 illustrates, matching the behavior seen in the case of an infinite periodic array. Also, the maximum force exerted by a single Sm-Co rectangle (i.e., the force when \( d = 0 \)) decreases as the size of the rectangle is reduced (see Fig. 1), again matching the behavior predicted by analytical modeling, and the total attraction increases linearly with the number of Sm-Co rectangles in a pattern.

Together, the modeling results teach us that the size of the rectangles in a pattern can be used to design the vertical extent of the magnetic attraction and the number of rectangles, along with the thickness and remnant magnetization of the hard magnetic film, can be used to determine the force restraining a pill fully within a recess Ni-side down. Further-more, the simulations predict that attractive forces well in excess of gravity can be expected.

High coercivity Sm-Co based thin films (\( \approx 250 \) nm) with in-plane remnant magnetization were deposited on Si (100) substrates by rf and dc sputterings.\(^{12}\) To obtain adherent films, the substrates were precoated with 30–90 nm of Cu and/or Ta by dc magnetron sputtering at a substrate temperature of 350 °C. The Sm (Co, Fe, Zr, and Cu) films were directly crystallized by thermalized sputtering at a substrate temperature of 350–400 °C. The Sm-Co based film deposited consisted of polycrystalline TbCu2-type grains oriented with the \( c \)-axes splayed about the substrate plane.\(^{12}\) The single phase nature of the Sm-Co based deposit allowed the magnetic properties to be unchanged by thermal annealing or subsequent device processing steps. The films were patterned using a dilute nitric acid etchant (15:500 by volume \( \text{HNO}_3 : \text{H}_2\text{O} \); room temperature; 5–10 s).

Assembly experiments were done using 5 μm thick 50 × 100 μm² InP pills with a 150 nm AuNiGe contact layer, 250 nm Ni soft magnetic layer, and 250 nm Au bonding layer;\(^{13}\) the calculated weight of these pills is \( \approx 2 \times 10^{-9} \) N. Target substrates were prepared with the Sm-Co films patterned into 10 × 10 arrays of rectangular target areas, each 45 × 95 μm² in size, separated from one another by 100 μm in each direction. There were four target area patterns: target area pattern 1 (TAP-1) was a solid 45 × 95 μm² rectangle; TAP-4 had four 5 × 10 μm² rectangles, one at each corner of a 45 × 95 μm² target rectangle; TAP-18 had eighteen 5 × 10 μm² rectangles around the target rectangle perimeter; and TAP-30 had thirty 5 × 10 μm² rectangles separated by 5 μm in each direction filling the target rectangle. The films were magnetized in-plane in the direction of the long rectangle axis; \( M_R \) from measured \( B-H \) curves was 0.5 ± 0.1 KG.

Recesses were produced on some of the target substrates by spinning a 5 μm thick layer of SU-8 2005 over the surface and patterning 60 × 110 μm² openings to expose the target rectangles. After final curing the resulting recesses have smooth vertical sidewalls and the SU-8 is resistant to acids, bases, and solvents. Recesses aligned over patterns TAP-18 and TAP-30 are shown in Fig. 2.

The first set of experiments used target substrates without recesses and pills with nickel on only one surface. The substrates were immersed in isopropyl alcohol (IPA) on the bottom of a Teflon beaker tilted at 20°, and a pill dropper was used to flow a mixture of pills and IPA over the substrate at a rate one drop every \( \approx 3 \) s for \( \approx 100 \) s. Each drop was estimated to contain \( \approx 50 \) pills and that \( \approx 1500 \) pills were flowed over the substrate in this 100 s cycle. The disposition of the pills was noted and the process was repeated several times. No pills were retained by pattern TAP-4, while TAP-18 and TAP-30 retained pills with their Ni-side down only. However, those pills could be reoriented and even knocked loose by other pills flowing by them, indicating the importance of supplementing magnetic forces with recesses for coarse alignment and shielding.

The second set of experiments used target substrates with recesses aligned as in Fig. 2 and pills with Ni on both surfaces. Also, TAP-4 was replaced by a new pattern, TAP-
are sufficient to retain pills, while 18 is too few, tells us that the force exerted by each rectangle falls between the weight of a pill divided by 30 and 18, i.e., 0.66 × 10⁻¹⁰ N ≤ force per rectangle ≤ 1.1 × 10⁻¹⁰ N. The force predicted at d = 0.25 μm separation (the thickness of the Au on the Ni layer) is 2–3×10⁻¹⁰ N (see Fig. 1) which is in reasonable agreement with the experimental observations. Still, this agreement must be viewed with some caution: First the force depends on M_r^2 and the measurements of M_r showed significant variation. Second, pills can be forced out of recesses by fluid forces as well as by gravity; so the retaining force must actually exceed gravity. Additional experiments are clearly needed to more fully model the assembly process.

Recently Sm-Co films with significantly better B-H curves (H_c: 5–8 kOe and 4πM_s: 8–11 kG) and higher in-plane remnant magnetization have been produced. It is expected that assembly using these films will require fewer and smaller rectangles to retain pills. Experiments are planned using these improved films with a wider variety of magnetic patterns and, using more numerosly, higher quality pills.

The results presented validate the hypothesis that patterned magnetic films, used in conjunction with recesses, can be used to advantage during fluidic assembly of microscale components. Also, readily available magnetic materials and standard processing are used so barriers to implementing this technology in practice are low. More research is needed on the orientation and retention, and on using magnetic patterns to achieve precision positioning and angular alignment, but the feasibility of using magnetic attraction to advantage in automated microscale self-assembly has been established.

Experiments using Pattern TAP-1 (a single 45 × 95 μm² Sm-Co rectangle) and recesses showed that this pattern exerts excessive attraction extending far above the substrate. Pills were held tightly in place even when they were only partially in a recess and were hard to dislodge with jets of solvent. Pills also adhered to pills already in a recess.

These behaviors were not seen with the patterns with small 5 × 10 μm² Sm-Co rectangles, although those patterns did all differ in their degree of retention. Pattern TAP-10, with 10 small rectangles, had the lowest rate of retention and after 24 cycles was just over 20% full. Pills could also be readily dislodged from recesses by jets of solvent. Pattern TAP-18, with 18 small rectangles, was slightly better than TAP-10 but was still only just over 30% full after 24 cycles. Pattern TAP-30, with 30 small rectangles, however, had a significantly higher rate of retention (>2×) and over 90% of the recesses were filled by pills after 14 cycles, with no stacking of pills or retention of pills partially in recesses. These results indicate that the combined force from 30 rectangles is sufficient to hold pills in recesses and that the attraction decreases quickly enough that inverted pills and pills only partially in a recess are not retained. As mentioned above, debris in the pill slurry precluded achieving 100% filling, but these results are already very significant.

Assuming that the pills came out of the recesses due to only to the force of gravity, the fact that 30 Sm-Co rectangles