Magnetically-Assisted Statistical Assembly - a new heterogeneous integration technique

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Abstract—— **This paper presents a new technique for the monolithic heterogeneous integration of compound semiconductor devices with silicon integrated circuits, and establishes the theoretical foundation for a key element of the process, tailored magnetic attraction and retention. It is shown how a patterned thin film of hard magnetic material can be used to engineer the attraction between the film and nanopills covered with a soft magnetic material. With a suitable choice of pattern, it is anticipated that it will be possible to achieve complete filling of recesses in the surface of fully-processed integrated circuit wafers, preparatory to subsequent processing to fabricate the nanopills into heterostructure devices integrated monolithically with the pre-existing electronics.**

***Index Terms* — optoelectronics, heterogeneous integration, self assembly, VCSELs, III-V heterostructures**

I. Introduction

This paper presents an approach to the heterogeneous integration of compound semiconductor devices (laser diodes, for example) with silicon integrated circuits. This new approach, called magnetically-assisted statistical assembly (MASA), combines statistical self-assembly with magnetic retention to locate compound semiconductor device heterostructures in shallow recesses patterned into the surface of an integrated circuit wafer. All of the recesses on the wafer are filled with heterostructures, and the wafer is then processed further to transform the heterostructures into devices monolithically integrated with the underlying circuitry. The details of this process are the subject of this paper and will be described below after a brief background discussion.

The importance of integrating different materials and different device functions, a process generally termed heterogeneous integration, is widely recognized [1-4]. So too are the problems inherent in combining different materials. Principal amongst those problems is that of thermal expansion coefficient differences because the thermal expansion mismatch between silicon, the primary material of interest for large-scale high-density integrated circuits, and III-V compounds, the materials of interest for optoelectronic and microwave devices and circuits, is very large. The difference between the thermal expansion coefficient of GaAs, for example, and that of Si is exceeds 4 x 10^{-6} ßC^{-1} [1]. To put this in perspective, the diameters of GaAs and Si wafers that are an identical 150 mm (6) at room temperature, will differ by 70 m at 100 ßC. Such large mismatches make it difficult to grow device-quality III-V heterostructures directly on silicon wafers, or to bond full wafers of III-V devices with full silicon integrated circuit wafers.

For the most part, heterogeneous integration today is done by using some variation of flip-chip solder-ball (or solder-bump) bonding to attach modest sized arrays of, for example, vertical-cavity surface-emitting lasers (VCSELs) on individual integrated circuit chips [4]. This approach works, but it also has serious limitations which lead one to look for a better alternative. In particular, the size of the device array that can be bonded depends on the bonding temperature, and is typically limited to a centimeter on a side. Also, for best results the substrate of the device array must be thinned and, ideally, totally removed leaving the devices in the array separated one from the other. This involves extensive additional processing. Finally, because the industry standard for silicon integrated circuit wafers is 200 mm in diameter, and for GaAs wafers it is 150 mm, bonding full wafers is impractical. One is forced to bond pieces of wafers and to use a tiling process to cover a full wafer.

The research group of the author at MIT has pursued a different method of optoelectronic integration they term the optical solder bump concept. The essential approach of the optical solder bump concept is to put compound semiconductor heterostructures in recesses in the surface of commercially-processed integrated circuit wafers and to then fabricate those heterostructures into devices (typically, but not exclusively, optoelectronic devices) monolithically integrated with the pre-existing VSLI-level electronic circuitry. This sequence is illustrated generically in Figure 1. There is a long successful history at MIT of doing monolithic heterogeneous integration in this manner using one of several techniques[1]. In the OPTOCHIP Project, for example, the Epitaxy-on-Electronics (EoE) technique was used to produce what are arguably the most complex OEICs in existence. More recently Aligned Pillar Bonding (APB) [1] has been introduced to further expand the range of materials and circuits that can be integrated. This paper introduces the MASA process, a new technique that combines the best features of the EoE and APB integration techniques, with the new freedom to monolithically integrate any semiconductor device on any substrate.

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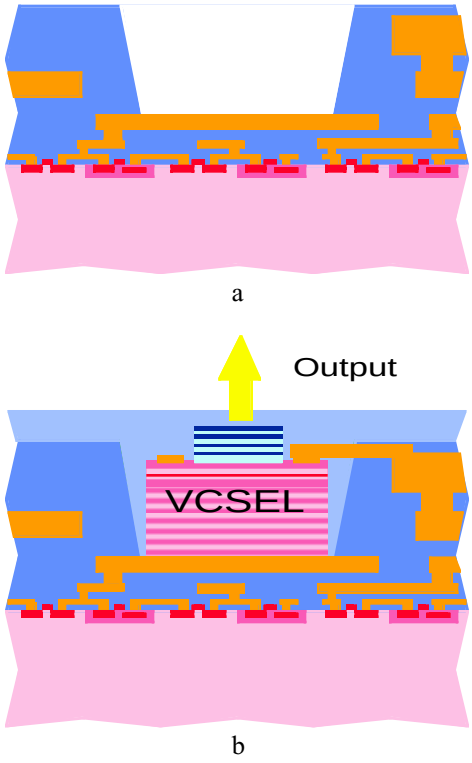

Figure 1 - The optical solder bump concept: a. A cross-section of one of the recesses formed in the dielectric layers covering a commercially-processed integrated circuit wafer. b. After compound semiconductor device heterostructures have been put into position filling the recesses, and processing to make completed devices (VCSELs in this illustration) has been completed.

An alternative approach to bonding ensembles of devices that are then divided into individual devices is to begin with individual devices and to attach each in its proper place on the integrated circuit surface. Such an approach sounds impractical at first, but upon further thought one realizes that it offers significant advantages once the assembly process is perfected. It circumvents the problem of smaller compound semiconductor wafer sizes, it can be used with any material with minimal concern with thermal expansion coefficient, and it can be used to assemble several different types of devices on a single substrate. Two approaches of this type are the DNA- and electrophoresis-assisted assembly techniques of Prof. S. C. Esener et al at the University of California at San Diego [5-7], and the fluidic self-assembly technique of Prof. J. S. Smith et all of the University of California at Berkeley [8-12]. These techniques each involve the location and attachment of many individual units on processed integrated circuits (or other electronic substrates), and their subsequent electrical interconnection. The individual units may be single devices, small assemblies of devices, or full integrated circuits. In the Esener approach a DNA-like polymer film is put on the individual units and a complementary film is patterned on the circuit (or a handle wafer) surface where the units are to be placed. The attraction between the two complementary DNA films then locates and holds the units in position [5]. In related work, this group has also used electrophoresis to attract and locate device units in place on a surface electrode pattern [6]. In the Smith approach, the individual units are etched to have slanted slides which match the size and shape of recesses formed in the substrate, the idea being that the units only fit in the recesses in one way [8-12]. A fluid carrying many units is flowed over the surface of the substrate, and gravity is relied upon to get the units into the recesses and to hold them there.

The MASA technique bears some resemblance to the work of Esener et al [5-7] and Smith et al [8-12], but differs in important ways. The uniqueness of the MASA technique lies in the methods used to locate and attach the individual units on their substrate, in the nature of the units being integrated, and in the amount of processing done subsequent to the assembly. As will be described in the following section, in the MASA process the units are highly symmetrical device heterostructure nanopills and they rest in similarly symmetrical recesses. Magnetic attraction is used to hold them in their recesses once they settle into place, and the final processing of the heterostructures into devices and their connection with the underlying circuitry is done photolithographically at the wafer level and in a pseudo-monolithic manner which takes full advantage of the economics of scale so important in integrated circuit processing, and which achieves the levels of complexity, reliability, and density common on modern VLSI chips.

II. The Nanopill Assembly Process

The MASA process begins with the preparation of the substrate and of the nanopills. The entire assembly process is shown schematically in Figure 2.

The substrate can be either the final integrated circuit wafer or an intermediate handle wafer. In either case, shallow recesses are patterned into the thick dielectric layers covering the wafer surface, as shown in Figure 2a. The depth of the recesses matches the thickness of the nanopills. A high coercivity magnetic layer, such as a cobalt-platinum alloy, is then deposited on the wafer and patterned in the bottom of the recesses. The pattern can be a simple array of stripes (this is the pattern analyzed in the following section) or it can be more complex. After the film is patterned it is magnetized normal to the wafer surface, and the wafer is ready for the statistical assembly step.

Formation of the nanopills begins with an epitaxial wafer. The heterostructure from which the devices being integrated are to be fabricated is grown under optimal conditions on the optimum substrate. The heterostructure will contain an etch-free layer which can be selectively etched away to free the device heterostructure from the substrate. This epitaxial wafer is next patterned into a close-packed array of cylindrical mesas, as shown

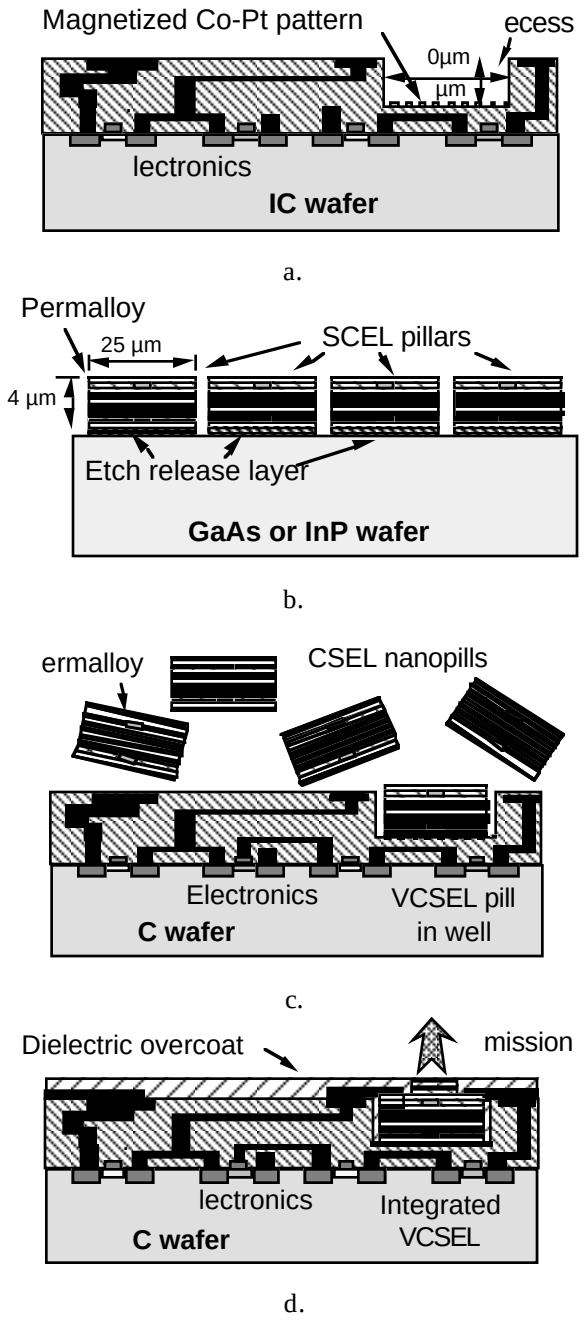

Figure 2 - The MASA process: (a) the processed IC wafer with the recesses prepared, and (b) the p-side down device wafer (in this case VCSELs) with pillars etched in a close-packed array; (c) statistical assembly of the freed nanopills in the recesses on the IC wafer; and (d) after completing device processing and integration.

in Figure 2b. These mesas are then etched free from their original substrate using a selective etch to form individual heterostructure device nanopills, as shown in Figure 2c. At some point in this processing a thin layer of nickel is also deposited on both sides of the nanopills.

During statistical assembly, the surface of a wafer prepared as described in the first paragraph of this section will be flooded with several orders of magnitude more nanopills than are needed to fill its recesses, as shown in Figure 2c. The large number of pills will mean that there are many pills in the vicinity of each of the recesses, and the symmetric nature of the pills will result in a high probability that a pill in the vicinity of a recess will fall into it. The result will be that the probability that a given recess is filled will be very nearly one, as illustrated in Figure 2d. The strong short-range magnetic attractive force which will come into play when a pill settles into a recess will keep the pill from being removed from the recess by gravity or by another nanopill or by the fluid used to flood the surface with nanopills. The process can be favorably compared to carrier trapping by deep levels in semiconductors.

As will be discussed in the theoretical analysis section below, the hard and soft magnetic layers will be engineered so that only those pills that go into a recess with the right side up (i.e., soft magnetic film side down) will stay there.

If the nanopills are assembled on a carrier wafer they can be transferred to the recesses on the circuit wafer by aligned pillar bonding [1]. If they are assembled directly on the circuit wafer this step is, of course, unnecessary.

Once the nanopills are on the circuit wafer they will be fixed in position using a polymer which will also fill in any voids on the surface surrounding the pills and planarize the surface. Processing of the heterostructures to convert them into devices and integrate them with the underlying electronics then proceeds using standard monolithic photolithographic processes. An important consequence of completing the processing only after the nanopills are in their final location is that the final alignment of the devices will de determined photolithographically and is independent of how precisely the pills are located in their respective recesses.

To summarize the features of the MASA process, the following list enumerates the key points:

1. The heterostructures from which the devices are fabricated are grown under optimal conditions on the optimum substrate and are then patterned into a close-packed array of cylindrical mesas, thereby resulting in the best possible material from which to fabricate devices, and using it with very little waste.

2. The nanopills are located in recesses which properly position the pills spatially and which keep the wafer surface planar for subsequent high resolution photolithographic processing.

3. The recesses and nanopills are highly symmetrical to facilitate the filling of recesses by nanopills. Both are cylindrical, with a large radius to height ratio.

4. Most of the processing of the nanopill devices is done after assembly meaning that the final alignment of the devices and circuitry is done photolithographically after the pills are fixed in position.

5. The magnetic attraction used to hold the nanopills in their recesses is a very short range force so it will hold a pill in a recess only after it is well positioned within the well. Because the pills themselves are not permanently magnetized, they will not stick together magnetically, nor will multiple pills stack up in a recess.

6. The process is designed to be conducted on commercially processed silicon integrated circuit wafers, taking full advantage of existing industrial processes and state-of-the-art technology. In can also be performed on a variety of other electronic substrates, including GaAs and InP IC wafers.

7. The entire process takes full advantage of wafer-level, batch processing to minimize cost, and to maximize performance, density, complexity, and reliability.

8. The IC wafer can be tested prior to assembly, and the device material can also be characterized before etching the nanopills free so that any defective regions on the epitaxial wafer can be avoided and those pills not used.

III. The Magnetic Retentive Force

The use of magnetic attraction to hold the heterostructure nanopills in their recesses is a key feature of the MASA technique. Consequently it is important to assess the retentive force that can be achieved by this method and to compare it with, for example, the force of gravity acting on a nanopill. It is also important to determine how quickly this force varies with separation to be certain that only nanopills well positioned in the well will be held in place while those that have only partially entered will be free to be moved about and have their position adjusted and corrected. This section presents the relevant modeling results.

For purposes of calculating the attractive force between a nanopill and a magnetized pattern at the bottom of a dielectric recess, one can consider the situation illustrated in Figure 3. The model system pictured in this figure consists, first, of a high-coercivity magnetic film of thickness t_1 which has a remnant magnetization, M_S, normal to plane and which has been etched into a pattern of equal width stripes and spaces with a period L (i.e. into stripes of width L/2 each spaced L/2 from adjacent stripes). A distance t_2 above this layer is a soft magnetic film of thickness t_3 with a magnetic permeability . In practice the first layer might be a cobalt-platinum alloy [13], and the second might be cobalt or nickel.

The magnetization of the first layer can be expanded in a Fourier series and written as

$$M_x(y) = \frac{M_S}{2} + \frac{2M_S}{\pi} \sum_{n\ \mathrm{odd}} \frac{1}{n} \sin\frac{2\pi ny}{L}$$

where the x-direction has been taken normal to the plane, the y-direction is in the plane normal to the stripes and spaces, and the z-direction is parallel to the stripes. The first term does not lead to any attractive force, and the sinusoidal terms act independently and their contributions sum to give an attractive force per unit area, F/A of:

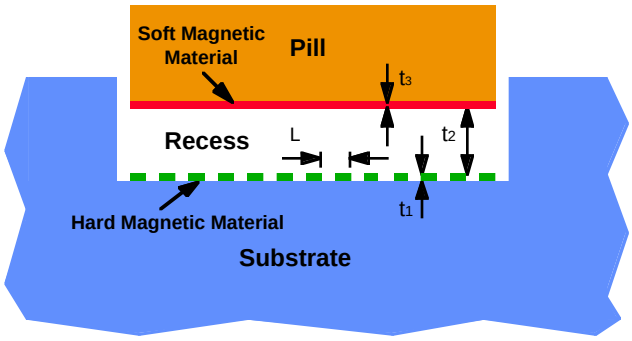

Figure 3 - The model system used to calculate the magnetic attractive force between the patterned polarized magnetic film at the bottom of the recesses in the target wafer and soft magnetic film on one surface of the nanopills.

$$\frac{F}{A} = \sum_{n\ \mathrm{odd}} \frac{\mu_0 M_S^2}{2\pi n^2} \left(1 - e^{-2\pi nt_1/L}\right) 2 e^{-4\pi nt_2/L} \frac{\sinh 2\pi nt_3/L}{\sinh\left[2\pi nt_3/L + \ln\left(\frac{\mu+\mu_0}{\mu-\mu_0}\right)\right]}$$

Examining this expression, we find that the n = 1 term is the most important for two reasons. First, the contributions of the higher order terms fall off as $1/n^2$, and, second, the t_2 term falls off very quickly with distance above the magnetized stripes for reasonable L and all n other than n = 1. The attractive force per unit area is thus approximately that due to the n = 1 term:

$$\frac{F}{A} \approx -\frac{\mu_0 M_S^2}{2\pi} \left(1 - e^{-2\pi t_1/L}\right) 2 e^{-4\pi t_2/L} \frac{\sinh 2\pi t_3/L}{\sinh\left[2\pi t_3/L + \ln\left(\frac{\mu+\mu_0}{\mu-\mu_0}\right)\right]}$$

An instructive way to consider this result is by examining its four terms individually. The first term depends on the saturation magnetization, M_S, of the permanently polarized layer. One can evaluate it for representative materials to determine the maximum attractive force possible as the value of the other terms approaches one. This is done in Table I for nickel, cobalt, and iron.

Maximum force, $\mu_0 M_S^2/\rho^2$		Value (nt/m^2)
Material	Nickel	3.0×10^4
	Cobalt	2.7×10^5
	Iron	3.7×10^5

Table I - The maximum attractive force per unit area (i.e. the multiplier term) for three magnetic materials: nickel, chromium, and iron. All other terms in the force expression have values between 0 and 1 (see Tables II, III, and IV).

The second term represents the dependence of the force on the thickness of the magnetized layer. Table II tabulates this term for layer thicknesses, t_1, of 0.2, 0.5, and 1.0 m when the pattern period, L, is 2, 5, and 10 m. Looking at this table one sees that this term will be 0.2, or more, when the layer thickness, t_1, is one tenth the pattern period, or greater.

Dependence on stripe height, t_1, and period, L		Stripe height, t_1		
		0.2 m	0.5 m	1.0 m
Period, L	2 m	0.22	0.63	0.92
	5 m	0.043	0.22	0.52
	10 m	0.014	0.073	0.22

Table II - The variation of the attractive force per unit area with the thickness of the magnetized layer, t_1, for several values of the pattern period, L.

The third term shows how the force decreases as the separation between the two magnetic layers increases. This term is tabulated in Table III for separations, t_2, between 0.2 and 10.0 m for pattern periods, L, of 2, 5, and 10 m. What is striking about this table is the quickness with which the force decreases with distance when the pattern period is small. For the present application it would be desirable to have a strong attractive force when the spacing is a micron or less, and very little when it is more than a few microns. This implies that the pattern period should be at least 5 m. The problem with making it much larger than 5 m, however, is that the number of stripes per recess will be small and the force, which was modeled assuming that the nanopill and recess were much larger than L in the y and z directions, will be less than calculated our equation. Consequently, 5 m is a good compromise value.

Dependence on period, L, and separation, t_2		Period, L		
		2 m	5 m	10 m
Separation, t_2	0.5 m	0.043	0.285	0.533
	1.0 m	0.002	0.081	0.286
	2.0 m	0.000	0.007	0.081
	5.0 m	0.000	0.000	0.002
	10.0 m	0.000	0.000	0.000

Table III - The variation of the attractive force per unit area with the separation between the magnetic layer and the magnetized layer, t_2, for several values of the pattern period, L.

The fourth, and final, term accounts for the parameters and characteristics of the soft magnetic layer on the nanopills. This term is tabulated in Table IV for a pattern period, L, of 5 m, layer thicknesses, t_3, of 0.2, 0.5, and 1.0 m, and relative layer permeabilities, μ/μ_0, of 50, 100, and 200. We see that for a relative permeability of 50 or more, a film thickness of 0.2 m is already sufficient to make this term greater than 0.75.

Dependence on layer thickness and permeability when L = 5 m		Layer thickness, t_3		
		0.2 m	0.5 m	1.0 m
Relative permeability, μ/μ_0	2 m	0.76	0.93	0.95
	5 m	0.86	0.98	0.98
	10 m	0.93	0.98	0.99

Table IV - The variation of the attractive force per unit area with the thickness of the magnetic layer, t_3, for several values of the relative permeability, μ/μ_0, when the pattern period, L, is 5 microns.

It is worth noting that the model assumes that the magnetization of the film does not saturate so it may over estimate the force when t_2 is very small, however it will give a good estimate until the magnetization does saturate. As will be clear below, by that point the magnetic attractive force will already be more than sufficient to retain the nanopills in their recesses.

Taken as a whole, the preceding examination of the terms in the force equation leads to a possible system design: a 0.5 m thick cobalt-platinum alloy layer (M_S = 1.8 Telsa) in the recesses patterned into stripes with a period of 5 m and a nickel layer on the nanopills 0.2 m thick. In this combination, the force per unit area on the nanopills will vary with the separation, t_2, as shown in Figure 4. For comparison, the gravitational force on a GaAs nanopill 6 m thick is approximately 0.3 nt/m ^{2}. This value, which one might consider to be representative of the largest force that would be available to pull the pill out of the recess (if, for example, the wafer is inverted) is indicated as a horizontal line in Fig. 4. It is exceeded for $t_2 < 4$ m, which is a comfortable

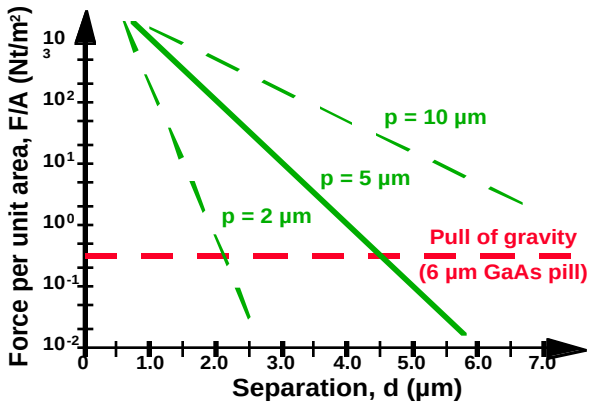

Figure 4 - The attractive force per unit area in Newtons per meter squared as a function of the separation, d in microns, for pattern periods of 2, 5, and 10 m. For comparison the pull of gravity on a 6 m thick GaAs nanopill is shown by the horizontal dashed line.

result. The attractive force on the pills will be negligible until they settle into a recess, but once they are in the recess they will be strongly held in place. The layer thicknesses in this design are very reasonable, and the stripes are easy to pattern, yet narrow enough that a typical recess 25 to 30 m in diameter will contain ten or more stripes.

The stripe pattern for the magnetic layer in the recesses is a particularly easy one to analyze, as well as to produce, but one can easily imagine that other patterns might offer advantages in terms of the attractive force they produce and their immunity to holding poorly located pills in a well. One can also imagine patterns that could center, and perhaps even orient angularly, the nanopills within a well with a high level of precision. The objective at this point, however, is to simply demonstrate that magnetic retention is an attractive technique to combine with statistical assembly to perform heterogeneous integration, and that much is clear from the preceding analysis of the simple stripe pattern.

IV. Conclusion

The MASA technique described in this paper offers a relatively simple process for integrating almost any compound semiconductor device, including VCSELs, GaInN LED s, detectors of all types, microwave devices, and many others, on commercially processed state-of-the-art integrated circuit wafers. It preserves all of the advantages monolithic integration and wafer-level batch processing, yet permits device and circuit testing at an intermediate stage so that assembly of bad units can be avoided, and yield greatly improved. The process differs in significant ways from similar techniques for statistical assembly, and overcomes the shortcomings of those approaches. Key unique features of MASA include (1) statistical assembly of highly symmetrical bilateral nanopills in similarly symmetrical recess on an IC wafer surface, (2) magnetic attraction to hold only properly positioned nanopills in place during assembly, and (3) final device processing, as well as integration, only after assembly.

Acknowledgments

The idea to explore magnetic attraction in statistical assembly originated as the author was listening to a talk Professor Markus Zahn of MIT gave in Spring 2000 on ferro-fluids. Prof. Zahn's subsequent interest in the concept, his generosity making time available for helpful discussions, and in particular his invaluable assistance in formulating the modeling problem and implementing the solution are all gratefully acknowledged. Several helpful discussions were also held with Professor Caroline Ross of MIT on the materials issues, including the various choices available for soft and hard magnetic materials and how one might go about depositing and patterning them. Finally, many discussions held with Professor Koichi Maezawa of Nagoya University in Japan while he was visiting at MIT from October 2000 to March 2001 are also gratefully acknowledged.

The experimental demonstration of the MASA assembly process is currently being pursued at MIT by two graduate research assistants, Mr. James Perkins and Mr. Joseph Rumpler. The current status of their efforts will be reviewed in the oral presentation of this paper at the Singapore-MIT Alliance symposium in January 2002.

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