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Modeling of Magnetic-Field-Assisted Assembly of Semiconductor Devices

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The process of magnetic-field-assisted assembly for the integration of semiconductor devices is described. A simplified model that is relevant to both magnetically assisted statistical assembly and magnetic-field-assisted assembly is presented. This two-dimensional, periodic model, which is a development of earlier work by Fonstad and coworkers, is solved using Fourier series, and an expression is found for the magnetic force of attraction between a soft magnetic layer and an array of permanently magnetized strips. The results show an exponential decrease of force with distance and the dependence of the force on other parameters such as layer thickness and spacing.

Key words: MEMS, microassembly, self-assembly, magnetic field, heterogeneous integration

INTRODUCTION

The heterogeneous integration of high-performance electronic devices, microelectromechanical structures (MEMS), and optoelectronic devices onto the same substrate is critical for the development of low-cost and high-performance, high-density microsystems.[1] Optical devices such as semiconductor lasers, light-emitting diodes, and efficient photodetectors can be made with III–V compound semiconductor materials, the direct bandgap of which endows them with many useful optical properties not found in silicon. The monolithic integration of optoelectronic devices on silicon complimentary metal oxide semiconductor (CMOS) circuitry is important for high-bandwidth optical applications.[2] In order to increase device performance and thus realize the potential of microsystems, it is well known that integration must occur at the microscale. At present, however, this remains a major challenge because of the fabrication sequences and material requirements of the different system components. The development of efficient wafer-scale assembly techniques can be used to overcome this difficulty and combine a variety of materials on a single chip.[3]

Current integration strategies often rely on pick-and-place serial assembly techniques,[4–6] which encounter speed and cost constraints in applications that require the assembly of large numbers of microscale components with precise positioning. In addition, surface forces must be carefully controlled to prevent unwanted adhesion of microscopic parts to each other or to tool surfaces. Because of these disadvantages, new low-cost parallel assembly techniques are being investigated and commercialized. As the dimensions of microelectronic, optoelectronic, and MEMS devices and systems decrease, and as their complexity increases, there is a need to use self-assembly and alternative integration techniques to simplify the manufacture of these devices.

MAGNETICALLY ASSISTED STATISTICAL ASSEMBLY (MASA)

Magnetically assisted statistical assembly (MASA) is a new technique for the monolithic heterogeneous integration of compound semiconductor

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devices with silicon integrated circuits.[7,8] This method uses statistical self-assembly with magnetic retention to locate compound semiconductor device heterostructures in recesses patterned into a wafer that also contains integrated circuits. In this method, selectively etched heterostructure devices or nanopills that contain magnetic layers are slurried over a substrate with patterned recesses of matching shapes and sizes. High-coercivity (permanent) magnetic layers situated at the bottom of the patterned recesses in the wafer locate and attach the nanopills to the recesses by the action of strong short-range magnetic attractive forces.[7,8]

MAGNETIC-FIELD-ASSISTED ASSEMBLY (MFAA)

Magnetic-field-assisted assembly (MFAA) is a proposed technique that is similar to MASA for the integration of microstructures onto silicon or other semiconductor wafers.[1,9] It is proposed as a low-cost, efficient, and reliable technique. The experimental approach is shown schematically in Fig. 1. Magnetic-field-assisted assembly begins with the separate preparation of the substrate and microcomponents. The substrate can be made from different materials, including glass, plastic, silicon, etc., depending on the desired application. For the integration of optoelectronics and MEMS devices with silicon integrated circuits, the starting substrate is an insulator, a semiprocessed wafer, or a final wafer that contains the required integrated circuitry. In all cases, recesses are patterned either into the dielectric layer covering the wafer surface or into the surface of the insulator, as shown in Fig. 1.

The recesses are formed on the surface of the substrate in such a way that the shape and depth of the recesses matches the shape and thickness of the microcomponents. A highly coercive ferromagnetic material, such as cobalt or nickel, cobalt-palladium or a cobalt-platinum alloy, is deposited on the insulator substrate or wafer. The layer is patterned to form either simple or complex features at the bottom of the recesses, and is subsequently magnetized to act as a host for the microcomponents.

Another approach to magnetic-field-assisted assembly using feed tape is illustrated in Fig. 2.[1] A substrate is patterned with multiple recesses that are shaped to receive correspondingly matched microcomponents. The feed tape is used to attach the microcomponents temporarily. On completion of magnetic self-assembly of microcomponents, individual microcomponents are attached to the matching recesses on the substrate. The feed tape portions are guided by wheels, and a magnet moves adjacent and parallel to the substrate. Equivalently, the substrate moves continuously relative to guide wheels. The feed tape portion that is parallel to the substrate executes little or no relative motion in the direction parallel to the substrate. The magnet executes either continuous or oscillatory movement in any direction with respect to the substrate. Exposed faces of the microcomponents on the feed tape are coated with material of high magnetic permeability, such as low-coercive unmagnetized ferromagnetic material. The coating becomes magnetized when placed in a magnetic field, and may include a physical or chemical agent for subsequent permanent bonding of microcomponents to the substrate. The magnetic field produced by the moving magnet magnetizes the coating, and the ensuing attractive force pulls the microcomponents off the tape and into recesses in the substrate. In this alternative method, microcomponents are pulled preferentially into recesses by several physical characteristics of the magnetic and contact forces.[1]

The direct magnetic-field-assisted assembly method described above does not rely on statistical randomness,[10] for example, pathways for assembling microcomponents can be rendered deterministic by application of moving magnetic fields. Its desirable attributes, when compared to statistical assembly, are scalability to rapid assembly of a plurality of microcomponents onto a host substrate and the avoidance of frustration effects that lead to assembly errors. Frustration occurs when the path from one or more microcomponents to a matching site on the substrate is blocked, or when one or more

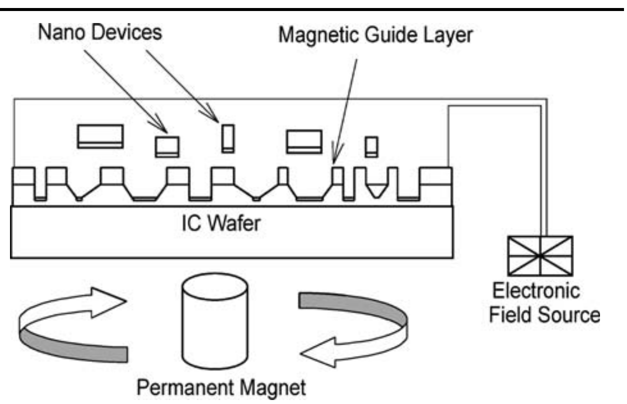

Fig. 1. A schematic of the magnetic-field-assisted assembly method of integrating microcomponents and integrated circuits.[1]

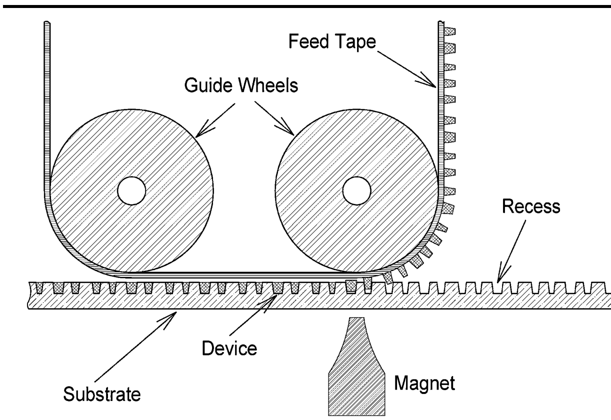

Fig. 2. A schematic of the magnetic-field-assisted assembly process using feed tape[1] (not to scale).

sites on the substrate remain unoccupied owing to the path being blocked. In addition, magnetic-field-assisted assembly does not require a liquid carrier medium. It provides a new technique for assembling and integrating microcomponents onto a silicon wafer or other substrate, and is carried out in such a manner as to avoid damaging any preexisting electronics. The process can also take full advantage of very large-diameter silicon wafers.[1]

MODELING OF MAGNETIC-FIELD-ASSISTED ASSEMBLY

A simplified model[7,8] that gives an estimate for the attractive force between an array of permanently magnetized strips and a soft magnetic layer in two dimensions is considered herein. A schematic of the model is shown in Fig. 3. The permanently magnetized strips have height t_1, width αL and are separated by air gaps of width $(1 - \alpha)L$. Here α is a parameter with $0 < \alpha < 1$. The soft magnetic layer has thickness t_3 and the vertical separation between the soft and permanent magnetic layers is t_2.

This is a generalization of a model originally proposed by Fonstad et al.[7,8] in the context of MASA. However, it is also relevant to MFAA, and the generalization introduced is that the magnetized strips and air gaps may have unequal width.

During the assembly process, since there is no electric field and there are no current sources, the model is magnetostatic and Maxwell's equations are:

$$\nabla \times \boldsymbol{H} = 0 \text{ and } \nabla \cdot \boldsymbol{B} = 0. \tag{1}$$

Therefore, there is a magnetostatic potential ϕ, such that $\boldsymbol{H} = -\nabla\phi$ everywhere. Considering linear, isotropic constitutive relations between the macroscopic magnetic field $\boldsymbol{H}$ and the magnetic induction $\boldsymbol{B}$, so that:

$$\begin{aligned} &\boldsymbol{B} = \mu_0 \boldsymbol{H} \quad \text{in air} \\ &\boldsymbol{B} = \mu \boldsymbol{H} \quad \text{in the soft magnetic layer} \\ &\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M}_0) \quad \text{in the permanent magnetic strips} \end{aligned} \tag{2}$$

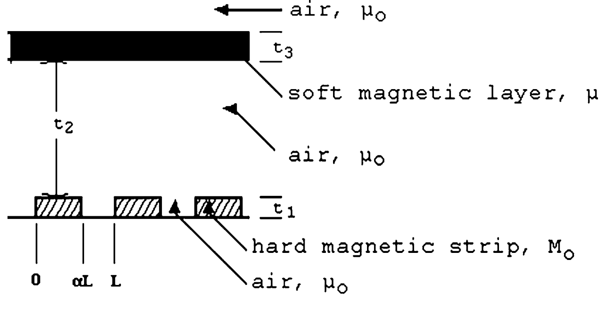

Fig. 3. A schematic of the model.

where μ_0 and μ are the (constant) permeability of air and of the soft magnetic material, respectively, and $\boldsymbol{M}_0$ is the known permanent magnetization of the strips.

In general, ϕ satisfies the Poisson equation, $\nabla^2\phi = \nabla\cdot\mathbf{M}_0$, with source term $\nabla\cdot\mathbf{M}_0$. Here, the magnetization $\boldsymbol{M}_0 = M_0\boldsymbol{j}$ is considered to be constant, where $\boldsymbol{j}$ is a unit vector in the y-direction normal to the substrate, so that the source term is zero, and the field equation becomes Laplace's equation:

$$\nabla^2\phi = 0. \tag{3}$$

Boundary conditions at the interface between air and either the soft or permanently magnetized material follow from Eq. 1, which imply that, at an interface, the tangential component of $\boldsymbol{H}$ and the normal component of $\boldsymbol{B}$ are continuous. In terms of the potential ϕ, using the constitutive relations (2), the boundary conditions are that ϕ is continuous and: at the interfaces, $y = t_1 + t_2$ and $y = t_1 + t_2 + t_3$, between the soft magnetic material and air

$$\mu_0 \partial_y \phi|_A = \mu \partial_y \phi|_S \tag{4}$$

at the vertical sides, $x = 0$, $x = \alpha L$ and $x = L$ etc., of the magnetic strips

$$\partial_x \phi|_A = \partial_x \phi|_P \tag{5}$$

at the horizontal sides, $0 < x < \alpha L$, $y = 0$ and $y = t_1$, of the magnetic strips

$$\partial_y \phi|_A - \partial_y \phi|_P = -M_0. \tag{6}$$

The subscripts A, P and S denote evaluation at the air, permanent or soft magnetic side of an interface, respectively. The only forcing or inhomogeneity in the problem for ϕ appears in this last boundary condition (6).

The problem is periodic, with period L in the x-direction, and can be solved by constructing Fourier series in each of the six regions shown in Fig. 3, and then applying the continuity and boundary conditions at the interfaces, with the further condition that ϕ is constant as $y \rightarrow \pm\infty$. This leads to a linear algebraic system for the Fourier coefficients, which can be found in closed form. Details of this part of the analysis are omitted for brevity.

An expression for the force acting on the soft magnetic layer follows by evaluating the integral of the Maxwell stress tensor over the layer's top and bottom surfaces. The general expression for the force $\boldsymbol{f}$ is:

$$\boldsymbol{f} = \mu \int_{\partial\Omega} \boldsymbol{H}(\boldsymbol{H}\cdot\boldsymbol{n}) - (1/2)(\boldsymbol{H}\cdot\boldsymbol{H})\boldsymbol{n}\, \mathrm{d}S \tag{7}$$

where, $\partial\Omega$ is a surface immediately outside the region of interest, $\boldsymbol{n}$ is its outward unit normal and μ is the local permeability. Then, in terms of ϕ, the force per unit length $\boldsymbol{F}$ is in the y-direction, i.e., normal to the substrate, and is given by:

$$\boldsymbol{F} = (\mu_0/2)\left(\int_{\text{top}} (\partial_y\phi)^2 - (\partial_x\phi)^2 \mathrm{d}x - \int_{\text{bottom}} (\partial_y\phi)^2 - (\partial_x\phi)^2 \mathrm{d}x\right)\boldsymbol{j} \tag{8}$$

where, the integrals over the top and bottom surfaces are evaluated as $y \to (t_1 + t_2 + t_3)^+$ and as $y \to (t_1 + t_2)^-$, respectively, with $0 < x < L$. A partial check on the expression for the Fourier coefficients is given by noting that the x-component of the force is zero.

When the constructed Fourier series are substituted in (8), the expression for the force per unit length $\boldsymbol{F}$ is:

$$\boldsymbol{F} = -\frac{\mu_0 L}{2}\sum_{n=1}^{\infty}\frac{M_0^2}{\pi^2 n^2}(1-\cos 2n\pi\alpha)e^{-4n\pi t_2/L} \times \left(1-e^{-2n\pi t_1/L}\right)^2 \frac{\sinh\frac{2n\pi t_3}{L}}{\sinh\left(\frac{2n\pi t_3}{L}+\ln\frac{\mu+\mu_0}{\mu-\mu_0}\right)}\boldsymbol{j} \tag{9}$$

This series converges rapidly as n increases. For $\alpha = ½$, the strips and air gaps are of equal width, and the series in Eq. 9 is well-approximated by its first term:

$$\boldsymbol{F} = -\frac{\mu_0 L M_0^2}{\pi^2}e^{-4\pi t_2/L}\left(1-e^{-2\pi t_1/L}\right)^2 \frac{\sinh\frac{2\pi t_3}{L}}{\sinh\left(\frac{2\pi t_3}{L}+\ln\frac{\mu+\mu_0}{\mu-\mu_0}\right)}\boldsymbol{j} \tag{10}$$

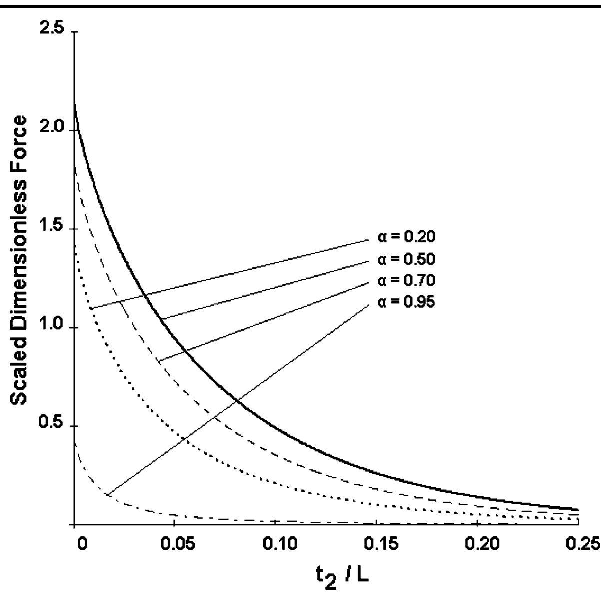

Fig. 4. Scaled dimensionless force versus t_2/L for different values of the length scaling parameter α. The magnitude of the force is a maximum when $\alpha = 0.5$ and approaches 0 as α approaches 0 or 1.

This is in accord with the expression given by Fonstad et al.[7,8]

Expressions (9) and (10) show an exponential decrease of the attractive force acting on the soft magnetic layer with dimensionless distance t_2/L. This is seen in Fig. 4, which shows a scaled dimensionless force, given by $\boldsymbol{F}$ divided by the n-independent factor on the right-hand side of Eq. 9, versus t_2/L for different values of α with $t_1/L = 0.5$, $t_3/L = 0.1$, and $\mu/\mu_0 = 50$. We find that the force is maximized when the parameter $\alpha = 0.5$ and $t_1/L = 0.5$, i.e., when the permanent magnets and air gaps have equal and square cross-section. Also, from (9) and (10), we see that when μ/μ_0 is large the attractive force is almost independent of the thickness of the soft magnetic layer t_3/L, unless t_3/L is exceptionally small, like μ_0/μ.

Figure 5 shows equipotentials ϕ = constant, with the same data $\alpha = 0.5$, $t_1/L = 0.5$, $t_3/L = 0.1$, and $\mu/\mu_0 = 50$ as in Fig. 4, for two different values of

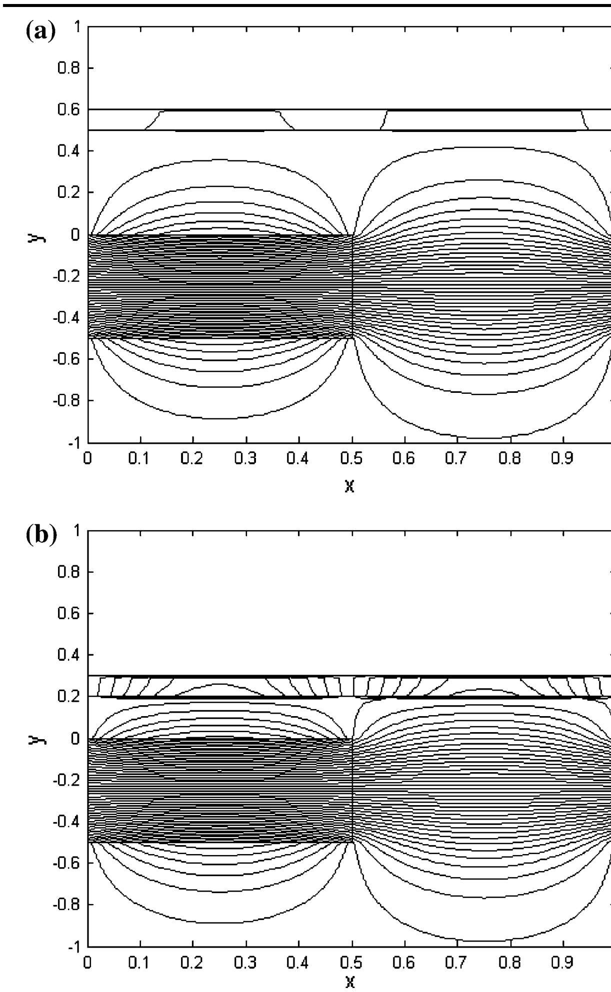

Fig. 5. Equipotentials ϕ = constant, with the same data $\alpha = 0.5$, $t_1/L = 0.5$, $t_3/L = 0.1$, and $\mu/\mu_0 = 50$ as in Fig. 4, for two different values of the vertical distance or separation between the permanent magnets and the soft magnetic layer, i.e., $t_2/L = 0.5$ in (a) and $t_2/L = 0.2$ in (b).

the vertical distance or separation between the permanent magnets and the soft magnetic layer, i.e., $t_2/L = 0.5$ in Fig. 5a and $t_2/L = 0.2$ in Fig. 5b. This agrees with the variation of the attractive force with separation distance given in Fig. 4. For $t_2/L = 0.5$, the separation is sufficiently large that the potential ϕ is nearly constant at the soft magnetic layer, so that the magnetic field $\boldsymbol{H}$ and attractive force are relatively weak. However, for decreased separation $t_2/L = 0.2$, the field at the soft magnetic layer is larger, particularly just below the layer's top and bottom surfaces.

CONCLUSIONS

A mathematical model that describes aspects of the magnetically assisted statistical assembly or magnetic-field-assisted assembly process for assembling semiconductor devices has been described. The model is two dimensional and magnetostatic. Its solution gives the attractive force between a periodic array of permanently magnetized strips and a soft magnetic layer, in terms of quantities such as the strength of the permanent magnetization and the dimensions of the system. This shows the exponential decrease of force with distance (separation) between the layers, and that the force is maximized when the width of the magnetized strips and the air gaps between them are equal and of square cross section. Attractive forces are maximum when assembled components are in contact and bonded together.

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REFERENCES

1. S. Shet, V.R. Mehta, A.T. Fiory, M.P. Lepselter, and N.M. Ravindra, *JOM* 56, 32 (2004).
2. H.-J.J. Yeh and J.S. Smith, *IEEE Photon. Technol. Lett.* 6, 706 (1994).
3. U. Srinivasan, D. Liepmann, and R.T. Howe, *J. Microelectromech. Sys.* 10, 17 (2001).
4. M.B. Cohn, K.F. Boehringer, J.M. Noworolski, A. Singh, C.G. Keller, K.A. Goldberg, and R.T. Howe, *Proc. SPIE, Vol. 3513, Microelectronic Structures and MEMS for Optical Processing IV*, ed. M.E. Mohamedi and H.P. Herzig (Bellingham, Washington, 1998), p. 2.
5. K.F. Böhringer, K. Goldberg, M. Cohn, R. Howe, and A. Pisano, *Proc. IEEE Int. Conf. Robot. Autom.* 2, 1204 (1998).
6. I. Shimoyama, *Proc. IEEE/RSJ Int. Workshop Intell. Robots Syst.* 2, 208 (1995).
7. C.G. Fonstad and M. Zahn, U.S. Patent No. 6,888,178 (3 May 2005); No. 6825049 (30 Nov 2004).
8. J. Rumpler, J.M. Perkins, and C.G. Fonstad, *Proc. IEEE Conf. Lasers Electro-Optics (CLEO)* 2, 2 (2004).
9. S. Shet, R.D. Revero, M.R. Booty, A.T. Fiory, M.P. Lepselter, and N.M.Ravindra, Proc. MS&T Symposium on Microstructural and Texture Requirements for Functional Materials, Organizers: A.Goyal, A.D. Rollett, E. Cerreta, and D. Field, Fundamentals and Characterization, Vol. 1, 451 (2006).
10. N.M. Ravindra, A.T. Fiory, and S. Shet, U.S. Patent 7,217,592 (15 May 2007).