High-Performance On-Chip Hot-Pressed NdFeB Hard Magnets for MEMS Applications

Yifan He [1], Chengju Yu [1], Samer Haidar[2], Mohsen Zaeimbashi [1], Gregory M. Stephen[3], Don Heiman[3], Yuyi Wei [1], Huaihao Chen [1], Xianfeng Liang [1], Cunzheng Dong [1], Jiawei Wang[1], Cheng Tu[4], Yi Zhang[5], Baoxing Chen[2], and Nian-Xiang Sun [1], *Fellow, IEEE*

[1]Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115 USA
[2]Analog Devices, Inc., Wilmington, MA 01887 USA
[3]Department of Physics, Northeastern University, Boston, MA 02115 USA
[4]School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
[5]College of Electronics and Information Engineering, Sichuan University, Chengdu 610064, China

In order to advance the potential of thick on-chip hard magnets for the micro-electro-mechanical system (MEMS), we investigate a new silicon molding technique to fabricate dry-packed NdFeB magnets, including a silicon compression tool, which enables the pressing step during silicon-compatible processing. This process delivers samples with a remanence of 0.42 T and an energy product of 38 kJ/m^3. Further studies of metal molding show that, for wax-bonding powder-based NdFeB magnets, the optimum fabrication condition is 300 °C and 425 MPa, giving a remanence of 0.54 T and an energy product of 61.7 kJ/m^3.

Index Terms—**Bonded magnet, hot-pressing, neodymium iron boron (NdFeB), permanent magnet.**

APPLICATIONS of permanent magnets are ubiquitous in the micro-electro-mechanical system (MEMS). However, there are numerous limitations with on-chip permanent mag- net fabrication [1], including limited fabrication conditions, non-repeatability, and requirements for lithography and dura- bility. Numerous efforts have been made to achieve high- performance on-chip hard magnets, among which NdFeB powder-based hard magnets have unique advantages in rema- nence, thickness, and fabrication repeatability. Wang *et al.*
[2] reported dry-packed hard magnets using different binding wax weight percentages, but the bonding was relatively weak and the maximum energy product was only 16.6 kJ/m^3. Romero *et al.* [3] proposed to use a polymer to bond the microparticles, where the as-fabricated thick films had a maximum of 0.7 T remanence magnetic flux density, but this method is unsuited for patterned magnets, which is indispensable for MEMS application. Screen printing [4],
[5] is also a commonly used fabrication method, but the magnet thickness is relatively thin among powder-based hard magnets. A major drawback of the powder-based magnet is its relatively low powder loading factor. For the dry-packing magnets, the powder is squeegeed into the pre-etched cavities, and without the pressure applied, there will be considerable space between the powders. By contrast, for the scenario of screen-printing or spin casting, the higher powder loading factor in the ink will increase its viscosity and, hence, the difficulty of the material deposition. The low loading factor ay cause a low sample density and, hence, low remanence. Moreover, the rotation and vibration of the unfixed particles g the demagnetizing process lead to low coercive fields. is work, we present a new dry packing methodology ltaneously incorporates the silicon mold and silicon
n tool, which first demonstrates the hot-pressing microfabrication. The maximum achieved rema- flux density is 0.42 T, and the maximum
s 38 kJ/m^3. Table I shows that the as- have superior performance among silicon sed magnets, as well as a relatively large
dry-packing methodology. These fea- s fabrication technique has potential applications requiring high mag-
rvesting and microwave devices. fabrication conditions, a sys- ed pressure and temperature e hard magnets fabricated
300 °C provided the
0 MPa did not alter
he fragility of the essing process is ocessing; how-
e utilized for ement.

μm) to r

Manuscript received August 19, 2020; revised October 28, 2020 and January 7, 2021; accepted January 31, 2021. Date of publication February 4, 2021; date of current version March 18, 2021. Corresponding author: N.-X. Sun (e-mail: nian@ece.neu.edu).
Color versions of one or more figures in this article are available at https://doi.org/10.1109/TMAG.2021.3057271.
Digital Object Identifier 10.1109/TMAG.2021.3057271

TABLE I

COMPARISON BETWEEN THIS WORK AND PERFORMANCE OF POWDER-BASED ON-CHIP MAGNETS FROM RELATED WORKS

Fig. 1. (a) Fabrication process of the dry-packed on-chip hard magnet. (b) Optical image of the dry-packed on-chip hard magnet.

percentage of 6%, where the melting point of the binding wax is approximately 80 °C.

As shown in Fig. 1(a), by using the same photolithography mask, positive and negative photoresists were adopted to make the silicon mold and the silicon compression tool by deep reactive ion etching (DRIE) process, respectively. The mold was etched as 500 μm deep cavities, while the compression tool is a silicon chip with some extrusions on top to apply the pressure during the fabrication. The mold and compression tools were fabricated in batch and diced into pieces afterward. The mixed powder was packed into the pre-etched cavities using a flat edge tool, followed by heating to 100 °C, and then, cooled down to room temperature. A 1000 Oe magnetic field was applied in an out-of-plane direction by a commercial bulk magnet, and a maximum of 10 MPa pressure was applied during the packing, heating, and cooling down process. The as-fabricated samples were then characterized in a Quantum Design MPMS SQUID magnetometer with a maximum of 5 T out-of-plane magnetic field applied at room temperature. The depth of the trench was measured by an electronic thickness drop indicator before and after powder mixture packing to calibrate the thickness of the sample. Dry-packed samples with no pressure and magnetic field applied were also fabricated as comparisons.

A series of hard magnet samples were fabricated in a 1/8 in diameter cylinder metal mold. The powder mixture mentioned above was packed into the mold and pre-heated to the target temperature, and the mold was placed in a hydraulic compression tool for a 10 s hot-pressing process, using various pressures applied for the samples fabricated under 100 °C and 300 °C. The samples were demolded, and the M H loop was carried out at room temperature using a vibrating sample magnetometer (VSM), with a maximum magnetic field of 2.2 T. Currently, the pressure applied in this process is not compatible with silicon molding process. The purpose of fabricating a series of hot-pressed hard magnets in the metal mold is optimizing the hot-pressing process flow on the fabrication condition for the hard magnet samples with sizes suitable for MEMS application.

III. RESULTS AND DISCUSSION

A. Dry-Packed NdFeB Hard Magnet on Silicon

In general, the magnetization of a single multi-domain particle includes domain wall motion and domain rotation process. When a sufficiently high magnetizing field is applied and removed, the magnetization of each domain rotates back to its original direction. Meanwhile, the domain wall distribution remains the same as it is in a saturated state, which renders a remanence Br. An out-of-plane magnetic field applied during the fabrication would align the magnetic powder such that the remanence Br induced by domain wall distribution has its maximum value.

Fig. 2. M H loop measurement results of dry-packing hard magnet fabricated with 0 Oe and 1000 Oe out-of-plane magnetic field applied.

Fig. 3. Optical image of the hot-pressed hard magnet and SEM image of its cross-sectional inner structure.

The optical image of an as-fabricated magnet is shown in Fig. 1(b), where the silicon mold was etched into 900 900 μm^2. The thickness of the sample is 0.36 mm. Due to the pressure applied during the powder packing process, the trench was not completely filled. The magnetic properties of on-chip, dry-packed magnets with and without 10 MPa pressure and 1000 Oe out-of-plane magnetic field applied are shown in Fig. 2. The sample processed with applied field and pressure yielded a remanence Br of 0.42 T and a maximum energy product of 38 kJ/m^3, namely, a 0.05 T and 10 kJ/m^3 improvement over samples processed without hot-pressing. The coercive field of the best samples was in the range of 690–710 kA/m.

It is worthy to mention that, to exclude the impact of different sample dimensions and reflect purely the material property, a thickness-dependent correction on demagnetizing field performed in (1) should be adopted to calculate the

Fig. 4. (a) M H loop measurement results of hot-pressed hard magnet fabricated under 300 °C and 425 MPa. (b) Energy product curve of hot-pressed hard magnet fabricated under 300 °C and 425 MPa.

effective applied field and energy product [11]. In (1), H_{eff} and H_{applied} are the effective and applied magnetic fields, respectively, N is the demagnetizing factor in the measurement direction, and M is the magnetization. The demagnetizing factor N in the vertical direction of cylinder samples is given in (2), where A is the ratio of the sample thickness and the sample radius [12]

$$H_{\mathrm{eff}} = H_{\mathrm{applied}} - NM \quad (1)$$

$$N_z = 1/\ 2A/\ \ \pi + 1\ . \quad (2)$$

A kink was observed in the demagnetizing curve of both samples; this was caused by the relatively poor bonding condition of on-chip hard magnets. The unbonded powder rotation would cause drastic magnetization decreasing in the low demagnetizing field region.

B. Hot-Pressed NdFeB Hard Magnet

As stated before, a series of hot-pressed samples were fabricated in the metal mold under different temperatures and pressures. The applied pressure ranged from 100 to 850 MPa and the processing temperature ranged from room temperature to 400 °C. The image of the sample is shown in Fig. 3. The diameter of the samples was 1/8 in, and the thicknesses were ranging from 0.56 to 1.25 mm, which gave demagnetizing factors ranging from 0.5 to 0.71. The thicknesses of these samples varied because of the fabrication condition difference and the material mass variation among the samples. The demagnetizing field correction would eliminate impacts on energy product calculation brought by the thickness variation.

The VSM measurement indicated that the sample with the best remanence Br and maximum energy product BHmax was fabricated under 300 °C and 425 MPa. The *M H* loop is shown in Fig. 4(a). A remanence Br of 0.54 T and a maximum energy product BHmax of 61.7 kJ/m^3 were observed. The better bonding condition compared to that of silicon-molding magnet eliminated the kink in the low applied field region. For the sample fabricated under 300 °C and 425 MPa, the energy product-effective magnetic field curve is depicted in Fig. 4(b). The maximum energy product was achieved under an effective demagnetizing field of 200 Oe.

1) Impact of Processing Pressure: According to the datasheet, the magnetic powder MQFP-B (D50 25 μm) has an apparent density of 2 g/cc, which is 26% of the density of NdFeB alloy. With the hot-pressing process, the density of the samples can achieve as high as 5.9 g/cc under 300 °C and 850 MPa. Fig. 5 shows the variation in the energy product and remanence as a function of pressure for samples processed at

Fig. 5. (a) Energy product BHmax of hot-pressed hard magnets fabricated under 300 °C and 100 °C with different pressures. (b) Remanence Br of hot-pressed hard magnets fabricated under 300 °C and 100 °C with different pressures.

Fig. 6. (a) Temperature-dependent sample density under 425 MPa. (b) Best hot-pressed hard magnet performance under different temperatures.

100 °C and 300 °C. However, the sample performance did not constantly increase with higher pressure with 100 °C and 300 °C temperature conditions; rather, the energy product was relatively constant in the range of 53–62 kJ/m^3 under 300 °C and 36–47 kJ/m^3 under 100 °C. This was presumably due to the smaller particle size brought by the intense pressing process. Compared with the powder average size of 25 μm, Fig. 3 showed a particle size in the range of 5–20 μm. The smaller particle size deteriorated the bonding condition, induc- ing a porous inner structure, and, consequently, diminished the demagnetizing performance in remanence and intrinsic coer- civity. This effect contradicted with high-pressure compres- sion, preventing further performance enhancement introduced by the hot-pressing process.

2) Impact of Processing Temperature: The variation of sample density with different temperature treatments under 425 MPa pressure and the impact of temperature on magnet performance are shown in Fig. 6(a) and (b), respectively. The increase in the temperature indeed imposed a higher density upon the samples. Under room temperature, the density was 4.58 g/cc, while a hot-pressing process under 400 °C delivered a density of 5.7 g/cc. Note that there were few additional compacting effects beyond 300 °C. However, while the hot-pressing can boost energy product more than 1.6 times, there was a clear indication that the remanence and the energy product were reduced when a temperature higher than 300 °C was applied. This could result from the poor bonding condition caused by the vaporization of bonding wax under high temperature and the formation of non-magnetic oxidized NdFeB compounds.

IV. Conclusion

In summary, NdFeB powder-based magnet samples were successfully fabricated with silicon molding and metal mold- ing, where bonding wax powder was mixed with the magnetic powder with a 6% weight percentage to consolidate the sample inner structure. For silicon molding, the mold and the compaction tool were fabricated with photolithography and the DRIE process. However, due to the fragility of the silicon mold, maximum pressure of 10 MPa was applied. An out-of-plane magnetic field of 1000 Oe and a processing temperature of 100 °C were also applied. SQUID magne- tometer results showed that the as-fabricated sample could achieve a magnetic remanence of 0.42 T and an energy product of 38 kJ/m^3 after demagnetization field correction. A series of cylinder magnet samples with 1/8 in diameter were fabricated under different pressures and temperatures in metal molds. It was shown that a higher pressure beyond 100 MPa did not increase the magnetic performance under both 100 °C and 300 °C processes, but 300 °C was found as the optimum fabrication temperature. The best sample was fabricated under 300 °C and 425 MPa delivered a magnetic remanence of 0.54 T and an energy product of 61.7 kJ/m^3. Considering the achieved small size and decent performance, the samples are potential candidates for MEMS application requiring an on-chip magnetic field. Developing sufficient positioning and bonding process flow are still demanded.

ACKNOWLEDGMENT

The work was supported in part by Analog Devices Incor- poration (ADI) and in part by the National Science Foundation under Grant DMR-1905662.

REFERENCES

[1] D. P. Arnold and N. Wang, "Permanent magnets for MEMS," *J. Microelectromech. Syst.*, vol. 18, no. 6, pp. 1255–1266, Dec. 2009.

[2] N. Wang, B. Bowers, and D. P. Arnold, "Wax-bonded NdFeB micro- magnets for microelectromechanical systems application," *J. Appl. Phys.*, vol. 103, Apr. 2008, Art. no. 07E109.

[3] J. J. Romero *et al.*, "Anisotropic polymer bonded hard-magnetic films for micro-electromechanical system applications," *J. Appl. Phys.*, vol. 99, no. 8, 2006, Art. no. 08N303.

[4] Z. C. Yuan *et al.*, "The production of Sr hexaferrite thick films by screen printing," *J. Magn. Magn. Mater.*, vol. 247, no. 3, pp. 257–269, Jun. 2002.

[5] S. Schwarzer, B. Pawlowski, A. Rahmig, and J. Töpfer, "Perma- nent magnetic thick films from remanence optimized NdFeB-inks," *J. Mater. Sci., Mater. Electron.*, vol. 15, no. 3, pp. 165–168, Mar. 2004.

[6] O. D. Oniku, B. J. Bowers, S. B. Shetye, N. Wang, and D. P. Arnold, "Permanent magnet microstructures using dry-pressed magnetic powders," *J. Micromech. Microeng.*, vol. 23, no. 7, Jul. 2013, Art. no. 075027.

[7] H. Li, T. J. Flynn, J. C. Nation, J. Kershaw, L. S. Stephens, and C. A. Trinkle, "Photopatternable NdFeB polymer micromagnets for microfluidics and microrobotics applications," *J. Micromech. Microeng.*, vol. 23, Apr. 2013, Art. no. 065002.

[8] B. G. Compton *et al.*, "Direct-write 3D printing of NdFeB bonded magnets," *Mater. Manuf. Process.*, vol. 33, no. 1, pp. 109–113, 2018.

[9] K. Tao *et al.*, "Micro-patterning of resin-bonded NdFeB magnet for a fully integrated electromagnetic actuator," *Solid-State Electron.*, vol. 138, pp. 66–72, Dec. 2017.

[10] S. Guan, B. J. Nelson, and K. Vollmers, "Electrochemical codeposition of magnetic particle-ferromagnetic matrix composites for magnetic MEMS actuator applications," *J. Electrochem. Soc.*, vol. 151, no. 9, pp. C545–C549, 2004.

[11] Y. Nakagawa and H. Kato, "Magnetic hysteresis and demagnetizing- field correction for rare Earth magnet materials," *IEEE Transl. J. Magn. Jpn.*, vol. 9, no. 6, pp. 177–184, Nov./Dec. 1994.

[12] M. Sato and Y. Ishii, "Simple and approximate expressions of demag- netizing factors of uniformly magnetized rectangular rod and cylinder," *J. Appl. Phys.*, vol. 66, no. 2, pp. 983–985, Jul. 1989.