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Additive Manufacturing of 3D Ceramic Structures for Electronic Applications of $YBa_2Cu_3O_7$

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Motivation

- Multichannel dc-SQUID systems have to be mounted inside a cryostat to be operated below T_c
- SQUIDs have to be encapsulated to prevent aging of the HTS materials
- Additive manufacturing offers the opportunity to develop arbitrary structures for sample holders and SQUID capsules to address problems of conventionally manufactured systems
- HTS materials can be printed to implement the SQUID wiring into the sample holders and the capsules

3D-Printing Gradiometer Modules

SQUID stability in water-vapor atmosphere

- Humidity sensor SHT11 from Sensirion AG, Switzerland
- Mounted in SQUID capsules made of PLA, Pertinax®, GFK, PETG, PEEK, PTFE, PPS
- Humidity: 95%
- Temperature: 25 °C
- Test duration: 70 hours
- Relative changes of humidity compared to environmental values are depicted in Fig.1
- We demonstrated low noise operation of sensitive dc-SQUID magnetometers with these materials [2], [3]
- A corresponding noise spectrum is depicted in Fig. 2
- Noise level: $\sqrt{S_B}$(77 K, 10 Hz) = 70 fT/√Hz
- The corresponding magnetic gradient noise at 7 cm baseline of the electronic gradiometer is 10 fT/(cm√Hz)

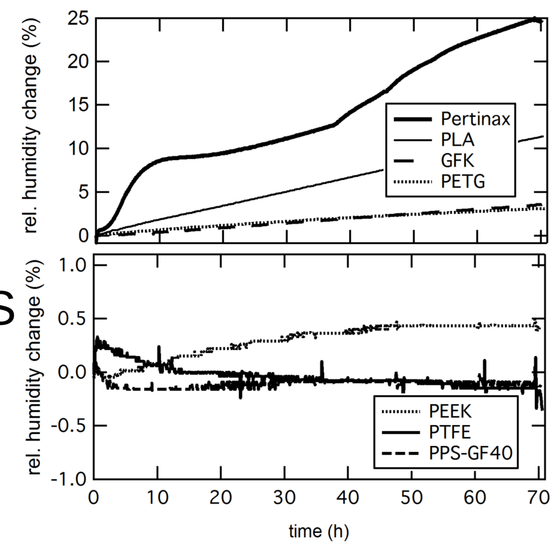

Fig. 1: Change of humidity in different types of capsules [1]

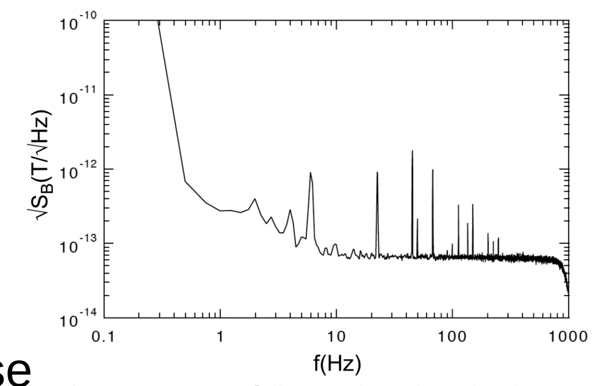

Fig. 2: Spectral flux noise density for a dc-SQUID magnetometer in the multichannel system [1]

3D-printer

- 3D-print of PLA plastic materials with 3D-printer RF1000 from Renkforce GmbH, Germany (Fig. 3(a))
- 3D-print of ceramic materials with 3D-printer RepRap Mendel and an in-house developed ceramic paste extruder (Fig. 3(b))

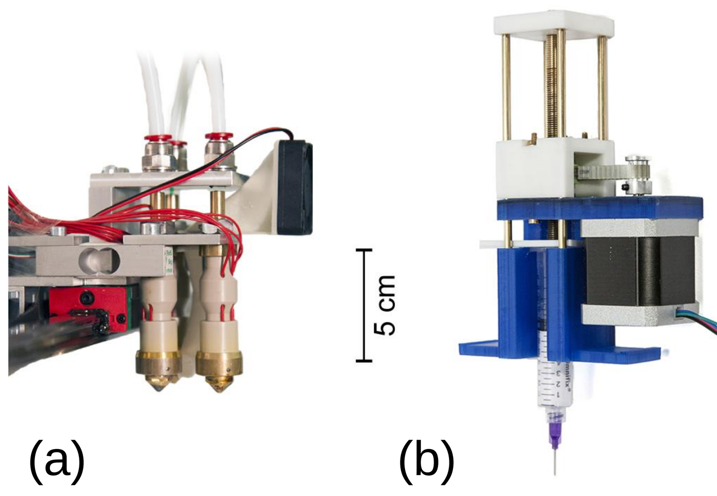

Fig. 3: Extruder for (a) fused deposition of plastic filament and (b) ceramic paste extrusion [1]

Gradiometer modules

- Subtractively and additively manufactured electronic gradiometer arrangements for SQUIDs which can be mounted in different planes are depicted in Fig. 4
- Additive manufacturing allows arbitrary structures to reduce heat conduction by thin rod arrangements
- Subtractively and additively manufactured capsules for humidity protection of the HTS SQUID magnetometers are depicted in Fig. 5
- Water tight and pressure resistant 3D-printed containers have already been realized from Nylon® filament [4]
- Very versatile and inexpensive SQUID modules for gradiometer arrangements can be achieved with additive manufacturing

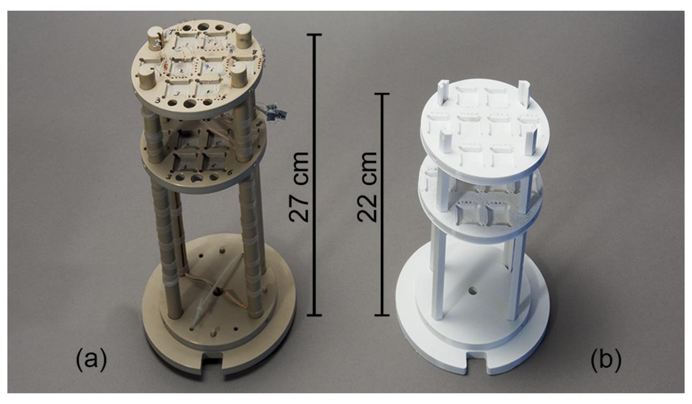

Fig. 4: Holder for multichannel system produced by (a) conventional subtractive manufacturing and by (b) additive manufacturing [1]

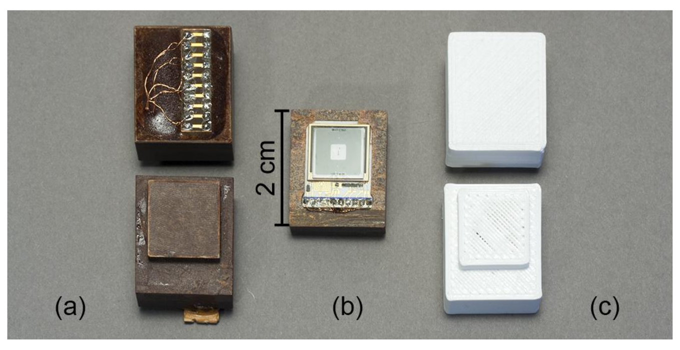

Fig. 5: (a) Conventional SQUID capsule for our multichannel system, (b) an opened capsule with a SQUID and (c) novel capsule produced by additive manufacturing [1]

Printing Superconducting Ceramics

- 3D-printed ceramic holders for SQUID capsules provide higher rigidity, better thermal insulation and water tightness with suitable materials
- $SrTiO_3$ as a substrate for $YBa_2Cu_3O_7$ is chosen due to the very good matching lattice constants, thermal expansion coefficients and negligible interdiffusion

Extruding ceramic paste

- $SrTiO_3$ as stoichiometric powder 99+% (metal basis) was dispersed in polyethylene glycol 200 (both Alfa Aesar)
- $YBa_2Cu_3O_7$ is prepared by milling of the stoichiometric compounds and by dispersing the powder in 1,2 Propandiol (Henry Lamotte) or in polyethylene glycol 200 (Alfa Aesar)
- The ceramic pastes are processed with the ceramic paste extruder

Sintering process

- The printing and drying processes are succeeded by mandatory sintering in an oxygen atmosphere to restore oxygen stoichiometry
- $SrTiO_3$ is sintered for 3.5 h at 1300 °C
- $YBa_2Cu_3O_7$ is sintered for 12 h at 950 °C

Test objects

- The electrical properties of 3D-printed $YBa_2Cu_3O_7$ lines are measured on a cubic and a planar structure (Fig. 6)
- On the cubic structure the $YBa_2Cu_3O_7$ lines are printed around the edges which cannot be achieved by other manufacturing methods

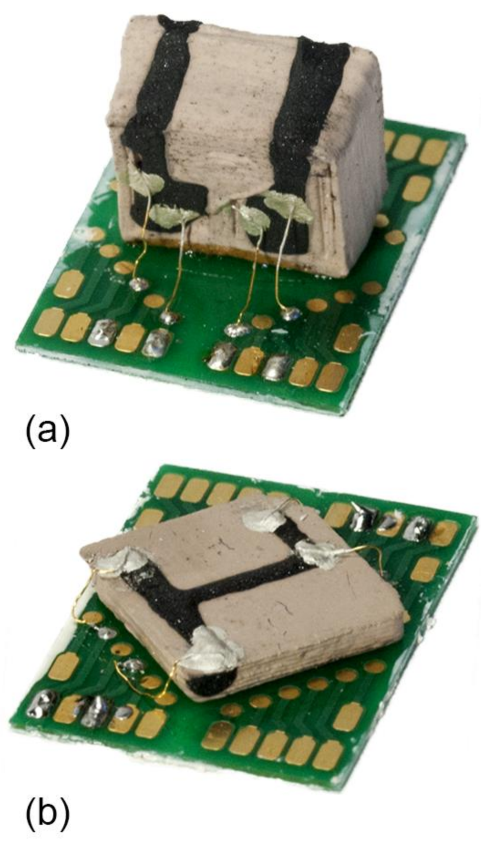

Fig. 6: (a) 3D-printed cube of 1 cm side length with 3D-printed superconducting $YBa_2Cu_3O_7$ line around the edges of the cube
(b) 3D-printed $YBa_2Cu_3O_7$ structure on a planar $SrTiO_3$ structure [1]

Properties of 3D-printed ceramics

- Critical temperature: $T_c \approx 84$ K
- Critical current: $I_c = 10$ µA
- Critical current density: $j_c(77\text{ K}) < 1$ A/cm²
- Superconducting transition temperature is determined from temperature dependent resistance measurement
- Structural properties are investigated by scanning electron microscopy (Fig. 7)
- Further optimizations are necessary to increase the density of the 3D-printed $YBa_2Cu_3O_7$ and to achieve better electrical properties

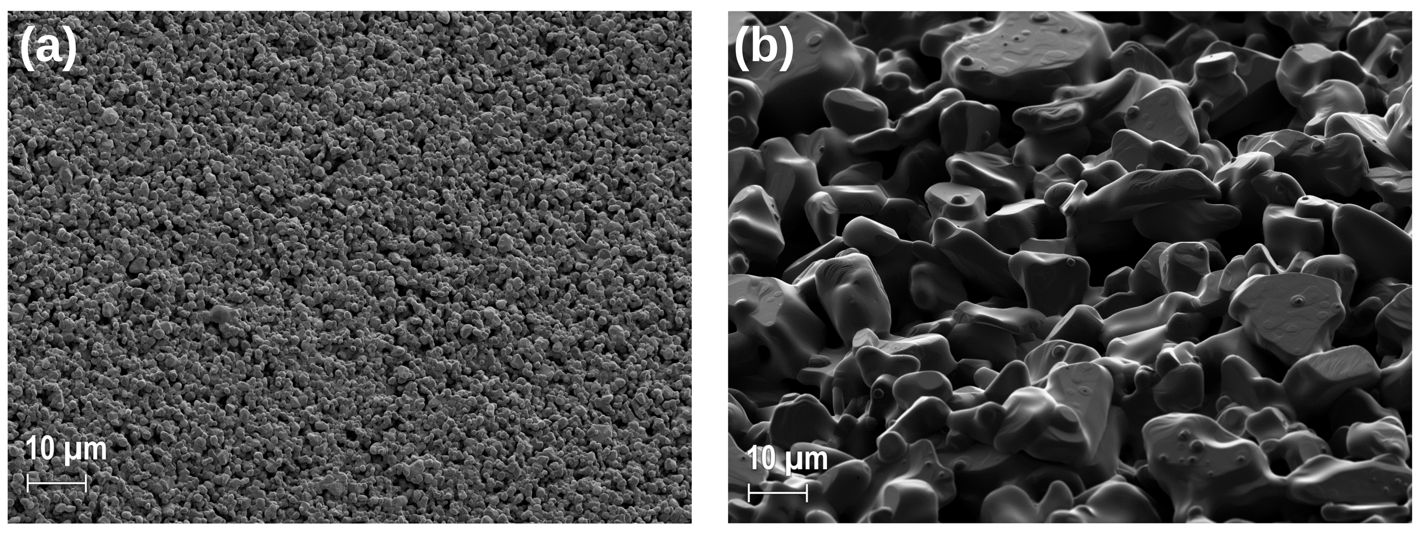

Fig. 7: Electron micrographs of 3D-printed and sintered (a) $SrTiO_3$ and (b) $YBa_2Cu_3O_7$ [1]

Acknowledgement

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References

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