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Abstract

Integrating a CVD graphene Hall cross beneath a PDMS microfluidic channel, we demonstrate real-time, label-free detection of individual ferrofluid droplets through transient Hall voltage measurements. The exceptional carrier mobility of graphene enables sensitive transduction of the stray magnetic field of passing droplets, yielding reliable detection and size discrimination via pulse-width analysis with a linear response across the full operating field range. The compact, planar architecture eliminates the need for bulky optical or inductive instrumentation, establishing graphene Hall sensors as a practical, chip-scale magnetic transducer for microfluidic sensing and droplet-based communication platforms.

Keywords: Graphene Hall Sensor, Molecular Communication, Microfluidic chip

Introduction

The Internet of Bio-Nano Things (IoBNT) envisions networks of nanoscale devices operating within physiological environments, where molecular and particulate carriers replace conventional electromagnetic signals [1]. Within this paradigm, droplet-based communication has emerged as a promising scheme, offering deterministic transport and higher throughput than diffusion-based approaches [2]. Ferrofluid droplets carrying magnetic nanoparticles are particularly attractive carriers due to their biocompatibility and detectable magnetic signatures in biological media [3], and their negligible magnetic background in physiological environments renders magnetic detection advantageous over optical methods for deeply implanted systems [4]; a distinction that becomes critical when sensing must occur silently, in situ, and without external illumination (Fig. 1).

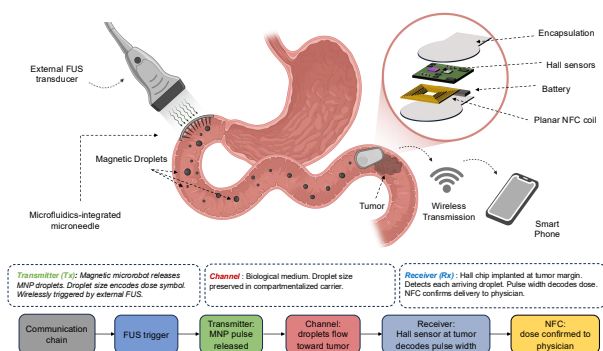


Figure 1. Conceptual illustration of a magnetic droplet-based communication system for in-body drug delivery, where a miniaturised Hall sensor receiver detects and decodes arriving magnetic droplets at the target site.

Realizing such systems, however, demands receivers that are not merely sensitive, but miniaturized, planar, and monolithically compatible with microfluidic architectures. Existing magnetic

readout approaches based on susceptometers and inductive coils [5,6] impose footprints and assembly constraints incompatible with implantable or lab-on-chip platforms. Hall-effect sensors offer a compelling alternative: a purely electronic, DC-operable transduction mechanism that converts localized magnetic flux into a measurable transverse voltage with no moving components [7]. Graphene elevates this principle further, as its monoatomic thickness and exceptional carrier mobility yield Hall coefficients that surpass conventional semiconductor implementations [8].

Yet graphene Hall sensors have not been applied to microfluidic droplet detection, leaving their considerable potential untapped at precisely the scale where it matters most. Here, we report a CVD graphene Hall cross integrated beneath a PDMS microfluidic channel that detects and size-discriminates individual ferrofluid droplets in real time through transient Hall voltage analysis, establishing a sensitive, chip-scale magnetic receiver architecture directly applicable to next-generation bio-nano communication and sensing systems.

Experimental

Device Fabrication

Fabrication began with patterning Ti/Au (5/50 nm) contacts on an n-type Si/SiO₂ substrate (525 μ m Si, 90 nm thermal oxide) by photolithography and electron-beam evaporation followed by lift-off. CVD-grown graphene was wet-transferred onto the pre-patterned electrodes and defined into Hall-cross geometries (100 μ m $\times$ 15 μ m) by photolithography and O₂ plasma etching. The active channel was encapsulated with 20 nm Al₂O₃ deposited by atomic layer deposition (ALD), and contact-pad windows were opened by selective wet etching. A PDMS microfluidic channel fabricated by soft lithography was plasma-bonded to the chip, completing the integrated device (Fig. 2).

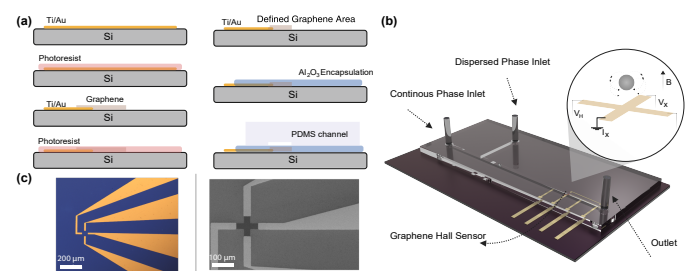


Figure 2. (a) Fabrication process flow of the graphene Hall sensor. (b) Schematic of the assembled device with integrated T-junction microfluidic channel and Hall measurement circuit. (c) Optical and SEM images of the fabricated graphene Hall cross.

Measurement Setup

Electrical characterisation was performed using a Keysight B2902B source measurement unit under perpendicular magnetic fields up to 40 mT generated by an external electromagnet. Water-based ferrofluid (EMG-705, Ferrotec) in silicone oil (100 cSt) was used as the droplet phase. Droplets were generated on-chip via a T-junction by independently controlling the dispersed- and

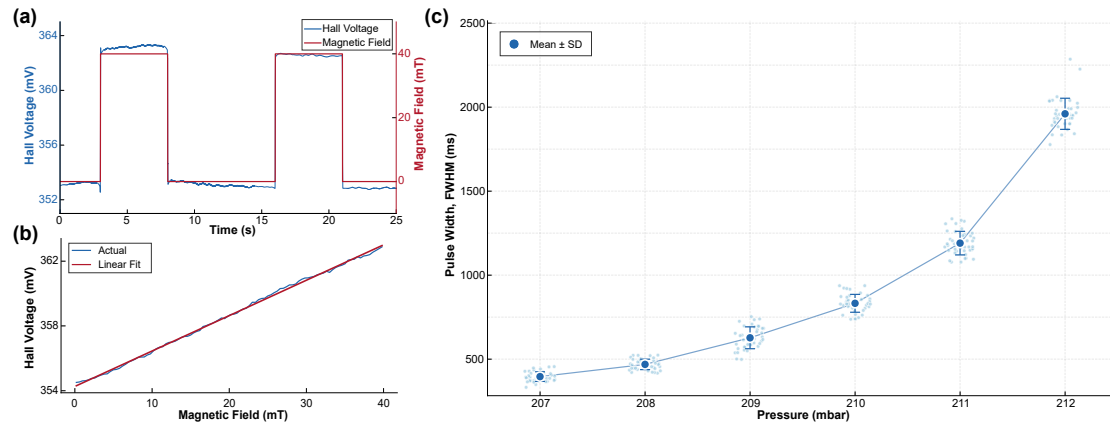


Figure 3. (a) Hall voltage response at $B = 0$ and $B = 40$ mT. (b) Hall voltage as a function of applied magnetic field with linear fit. (c) Mean pulse width ($\pm$ SD, $n = 40$) as a function of dispersed-phase pressure.

continuous-phase pressures, and the Hall voltage was recorded continuously as droplets transited over the sensor.

Results and Discussion

Sensor Characterisation

The Hall-cross geometry and contact integrity were confirmed by scanning electron microscopy (Fig. 2c). Electrical characterization under controlled out-of-plane magnetic fields revealed a linear Hall voltage response across the full 0–40 mT operating range (Fig. 3b), from which a sensitivity of 218.5 mV/T was extracted. This linear behaviour confirms the suitability of the graphene Hall cross as a quantitative magnetic transducer under the low-field conditions relevant to ferrofluid droplet detection.

Droplet Detection and Size Discrimination

Receiver performance was evaluated by varying the dispersed-phase pressure from 207 to 212 mbar while maintaining the continuous phase at 220 mbar, producing droplets of systematically increasing size. Each passing droplet induced a transient Hall voltage pulse (Fig. 3a), confirming real-time detection without optical access or additional labelling. As shown in Fig. 3c, the mean pulse width increases monotonically from 396 to 1960 ms with pressure, with clearly separated distributions at each operating point ($n = 40$ droplets per condition). The tight, non-overlapping distributions confirm both the stability of on-chip droplet generation and the repeatability of the Hall voltage read-out, demonstrating reliable size discrimination across a nearly five-fold dynamic range.

Conclusions

We have presented a chip-integrated graphene Hall sensor capable of detecting and size-discriminating individual ferrofluid droplets in real time through transient Hall voltage analysis. The device achieves a sensitivity of 218.5 mV/T with a strictly linear response up to 40 mT, and resolves droplet sizes across a nearly five-fold pulse-width dynamic range with non-overlapping distributions, without optical access, external labelling, or bulky instrumentation. These characteristics, combined with the planar, CMOS-compatible architecture, position graphene Hall sensors as a compelling building block for next-generation lab-on-chip diagnostics, implantable magnetic sensing, and miniaturised receivers in bio-nano communication networks. Looking forward, implementing structured modulation schemes and multi-sensor array configurations will be key steps toward a fully integrated, programmable droplet-based communication platform operating

within physiological environments.

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