A brief review on energy recycling from thermal fluctuations

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outline

A story in three chapters

chapter I: motivation. Energy recycling

chapter II: size does matter, or, recycle this!

chapter III: getting real

epilogue

erratum

Chapter I

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A micro electromagnetic generator for vibration energy harvesting

S P Beeby[1], R N Torah[1], M J Tudor[1], P Glynne-Jones[1], T O'Donnell[2], C R Saha[2] and S Roy[2]

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ambient noise “waste” energy

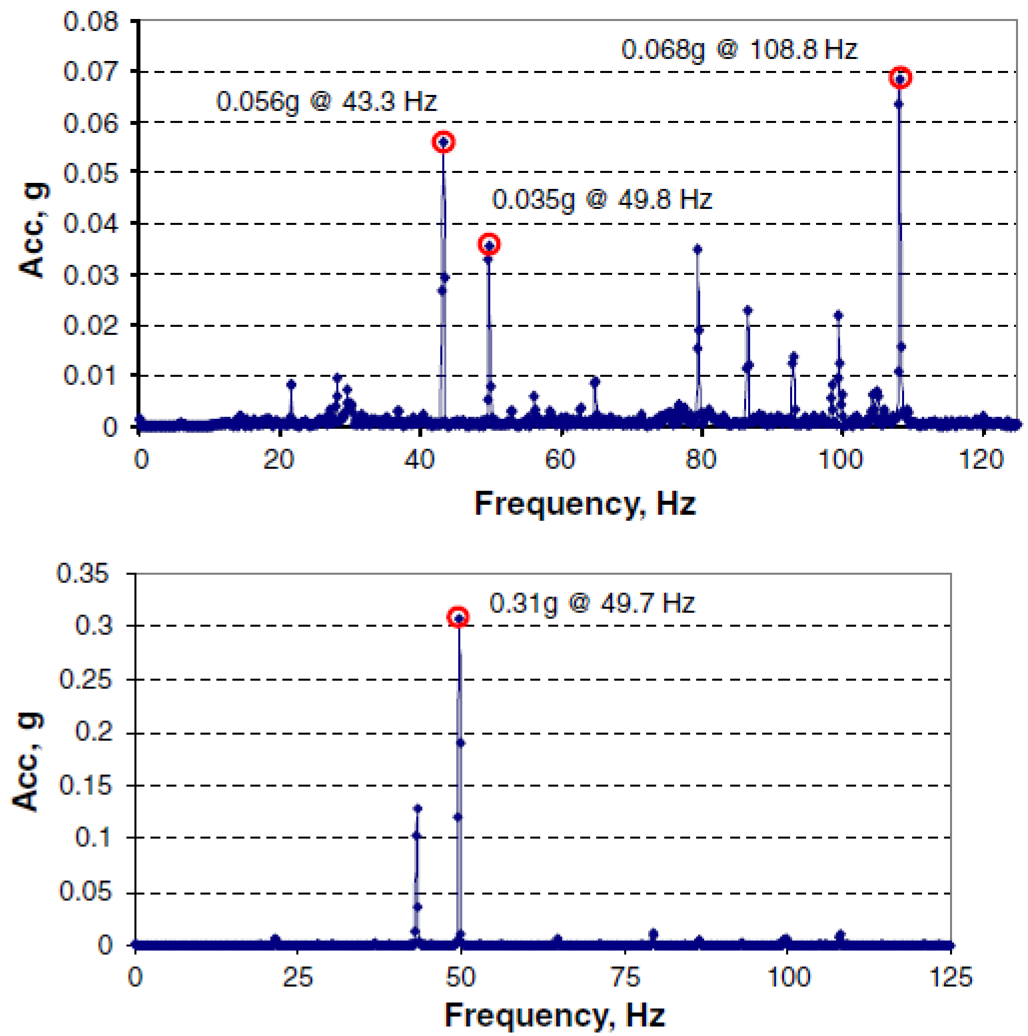


Figure 2. Example vibration spectra from compressor application (top plot from compressor enclosure, bottom plot from compressor).

energy "scavenger"

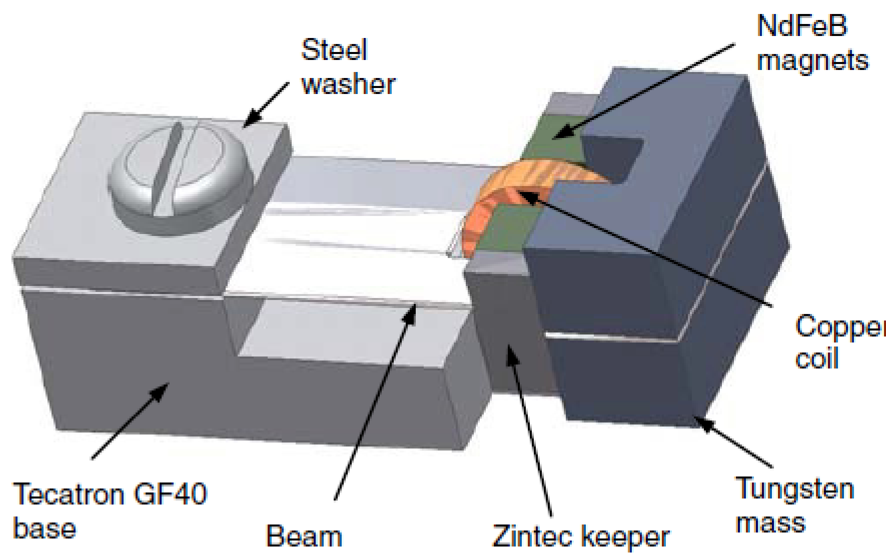
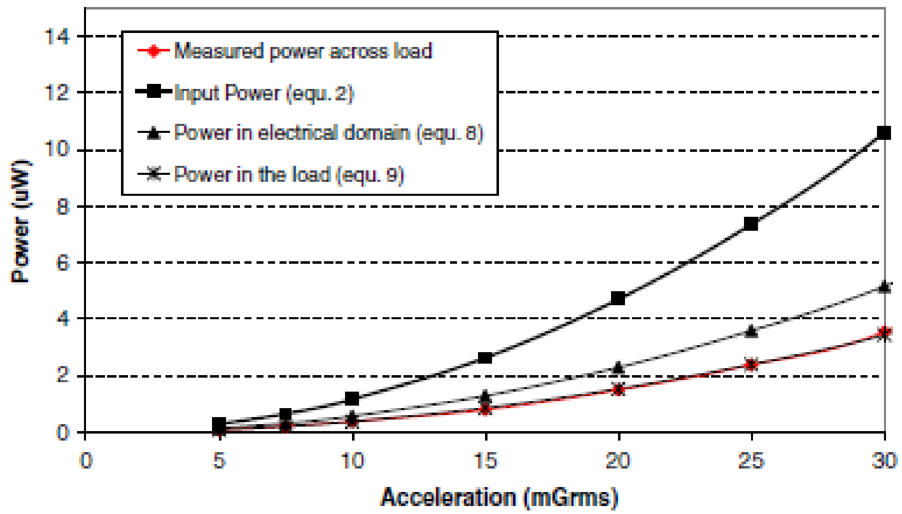


Figure 4. Micro cantilever generator.

Table 1. Coil parameters.

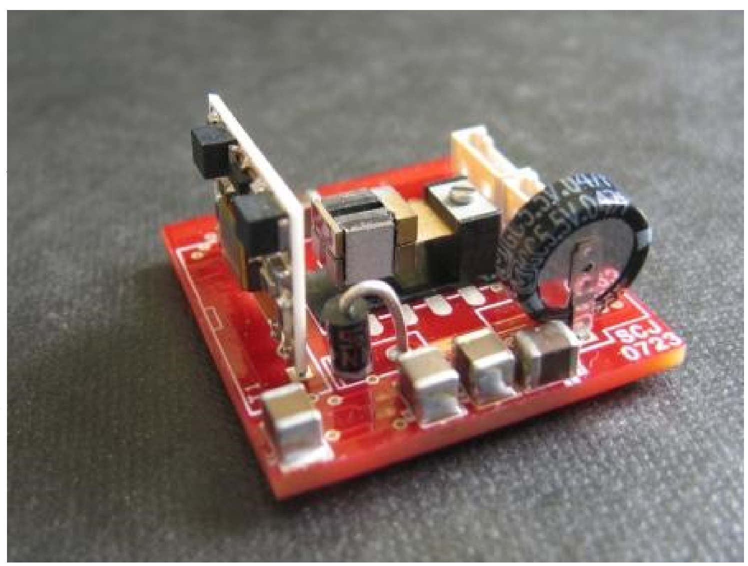
Coil	Wire diameter, ϕ (μm)	No. of turns	R_{coil} (Ω)	Fill factor
A	25	600	100	0.67
B	16	1200	400	0.45
C	12	2300	1500	0.53

it's been done and it works!



about 30% efficiency!

Figure 14. Comparison of theoretical and measured power output.



related work by other groups

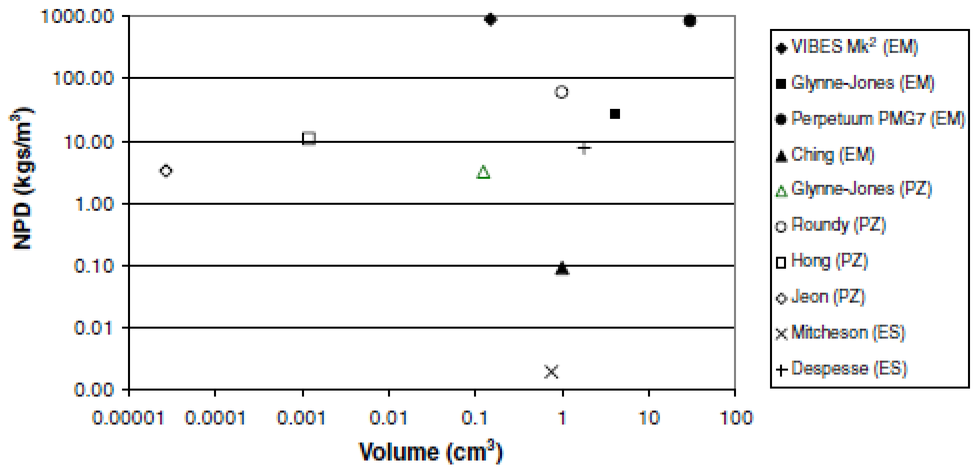


Figure 15. Normalized power density versus device volume.

Table 3. Comparison of generators.

Generator[a]	Freq (Hz)	Acceln (m s^{-2})	Inertial mass (g)	Volume (cm^3)	Power (μW)	NPD (kgs m^{-3})
VIBES Mk2 EM	52	0.589	0.66	0.15	46	883.97
Glynne-Jones [13] EM	99	6.85	2.96	4.08	4990	26.07
Perpetuum [14] EM	100	0.400	50	30	4000	833.33
Ching [15] EM	110	95.5	0.192	1	830	0.09
White [16] PZ	80	2.3	0.8	0.125	2.1	3.18
Roundy [17] PZ	120	2.5	9.15	1	375	60.00
Hong [18] PZ	190	71.3	0.01	0.0012	65	10.67
Jeon [19] PZ	13 900	106.8	2.20×10^{-07}	0.000 027	1	3.25
Mitcheson [20] ES	30	50	0.1	0.75	3.7	0.002
Despesse [21] ES	50	8.8	104	1.8	1052	7.55

[a] Generators are labelled by technology: EM, electromagnetic; PZ, piezoelectric; ES, electrostatic.

Chapter II

Now, what if ...

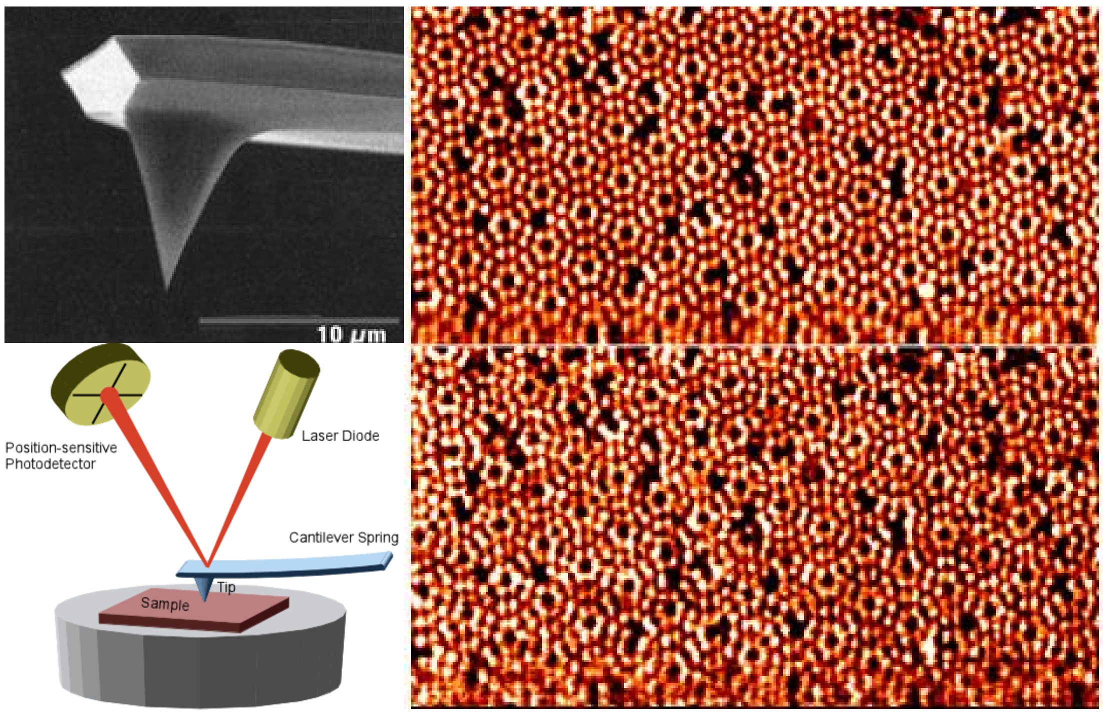
we make it (a lot) smaller

ambient noise $\longrightarrow$ thermal fluctuations

(a.k.a. Brownian motion)

the tale of an AFM tip

An Atomic Force Microscope can resolve 0.1 to 10 nm.



UHV

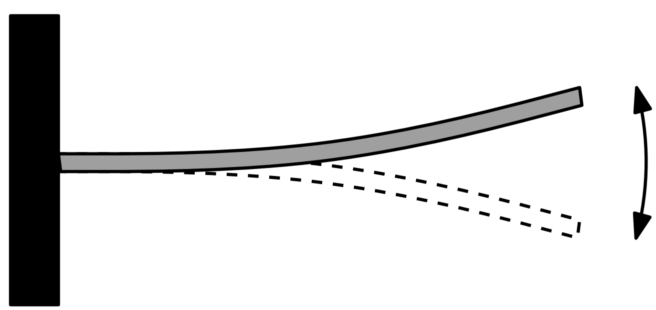
ULT

Thermal fluctuations impose a fundamental resolution limit

the tale of an AFM tip

A good tip thermal-fluctuates about 3 Angstrom (0.3 nm) at room temperature

Tips can be magnetic (can have a permanent magnetic moment).

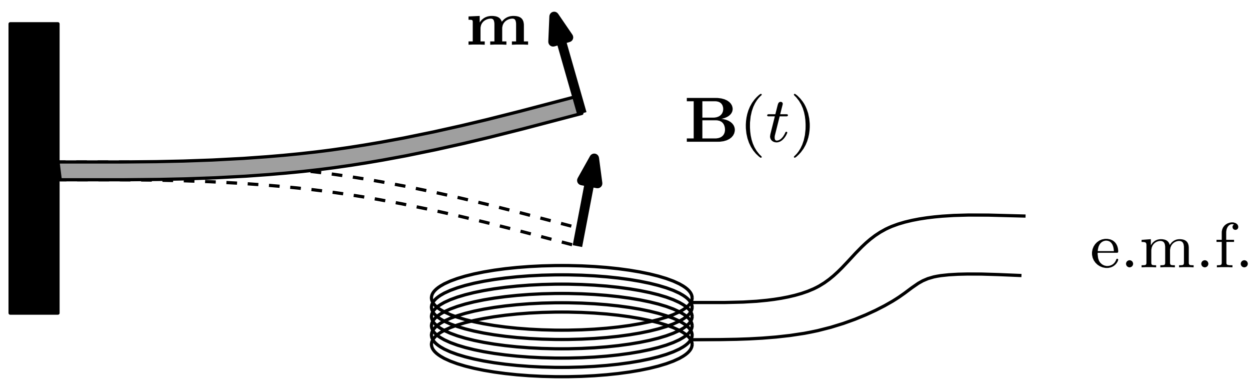


amplitude of the fundamental normal mode

“Bad” tips could fluctuate a few nanometers.

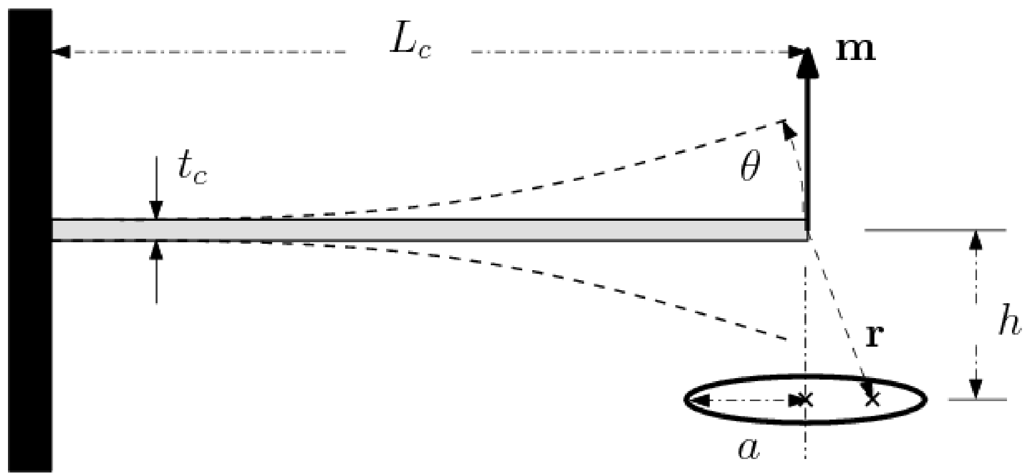
a small electromagnatic generator

just add a coil to the picture



Brownian motion induced electromotive force

the missing link: a (very) small coil



$$\mathbf{B}(\mathbf{m},\mathbf{r}) = \frac{\mu_0}{4\pi r^3}\left[3(\mathbf{m}\cdot\hat{\mathbf{e}}_r)\hat{\mathbf{e}}_r - \mathbf{m}\right]$$

$$\Phi_B = \int_{\mathbf{A}} \mathbf{B}\cdot d\mathbf{A} = \frac{\mu_0 m}{2}\frac{a^2}{(a^2+h^2)^{3/2}}$$

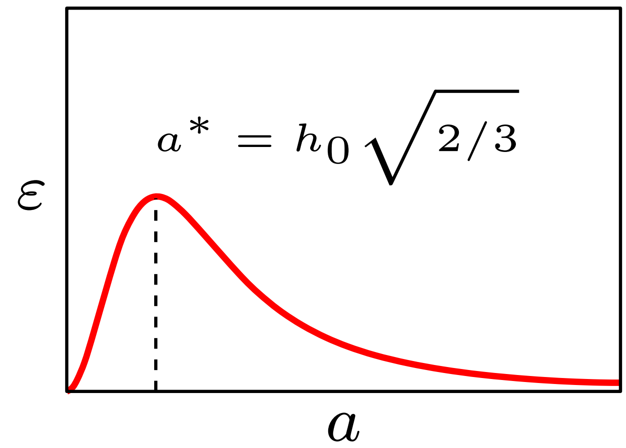
$$\varepsilon = -\frac{d}{dt}\Phi_B$$

$\mathbf{m}$ = magnetic moment (dipole)
a = loop radius
h = proximity (loop center - tip)

the missing link: a (very) small coil

$$h \to h_0 + k\cos\omega t \quad k \ll h_0$$

$$\varepsilon_{RMS} \approx \frac{3\mu_0 m\omega}{2\sqrt{2}} \frac{a^2 h_0 k}{(a^2+h_0^2)^{5/2}}$$



tipical values

Si cantilever ($400 \times 40 \times 0.8\ \mu$ size)
natural frequency: $\omega = 9.4 \times 10^4$ Hz
magnetic moment $m = 9.3 \times 10^{-7}$ (10^{17} spins)
proximity $h_0 = 1\ \mu$
amplitude $k = 1$ nm.
loop radius $a = 5\ \mu$

$$\varepsilon_{RMS} \approx 3.98 \times 10^{-7}\ \text{V}$$

($a^* \approx 0.8\ \mu$, $\varepsilon^* \approx 10^{-5}$ V)

times N !!!

Chapter III

$$Re\ \{\cdots\}$$

intrinsic noise

electrical resistance makes intrinsic (Johnson's) noise

$$V_n = \sqrt{4k_B T R \Delta f}$$

tipical values for a single loop, using a gold nanowire

loop radius $a = 5\ \mu$
wire diameter $\phi = 50$ nm
meassuring bandwidth $\Delta f = 1$ Hz
room temperature

$$V_n \approx 2.4 \times 10^{-9}\ \mathrm{V}$$

the induced EMF should be about two orders of magnitude larger than the noise !

remember $\varepsilon_{RMS} \approx 3.98 \times 10^{-7}$ V times N !!!

real wires

ARTICLES

Lithographically patterned nanowire electrodeposition

E. J. MENKE, M. A. THOMPSON*, C. XIANG*, L. C. YANG AND R. M. PENNER†
Institute For Surface and Interface Science and Department of Chemistry, University of California, Irvine, California 92679-2025, USA
*These authors contributed equally to this work
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real wires

ARTICLES

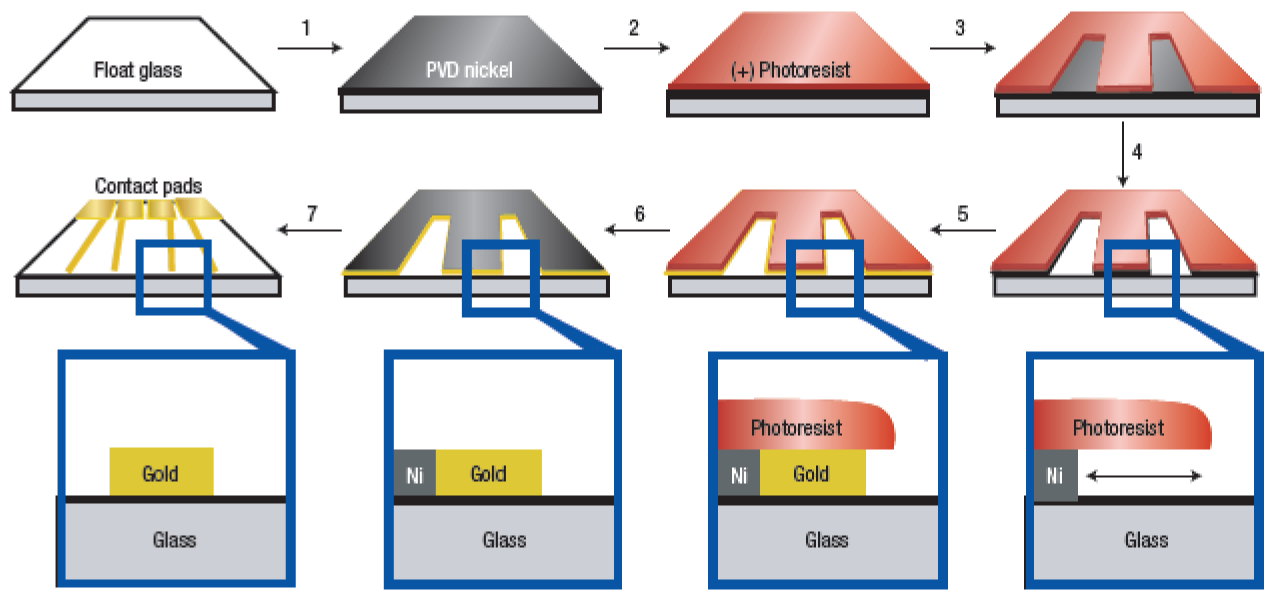
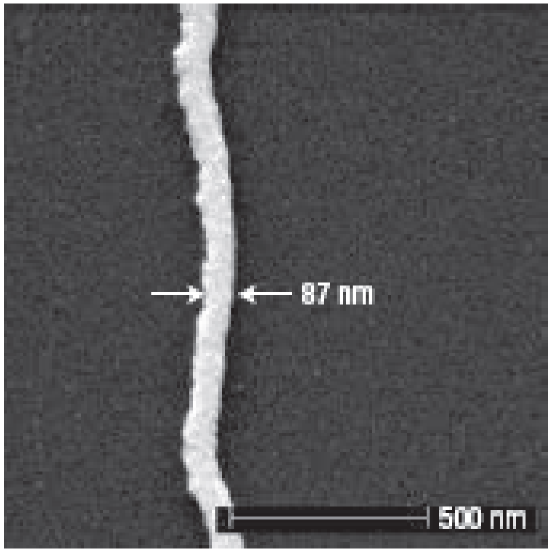
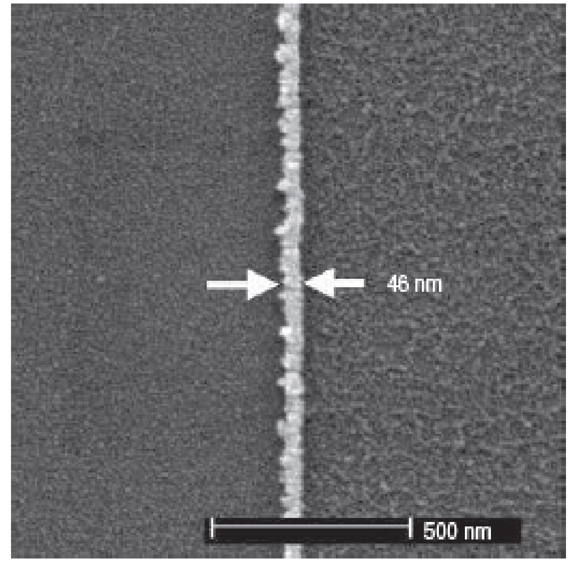


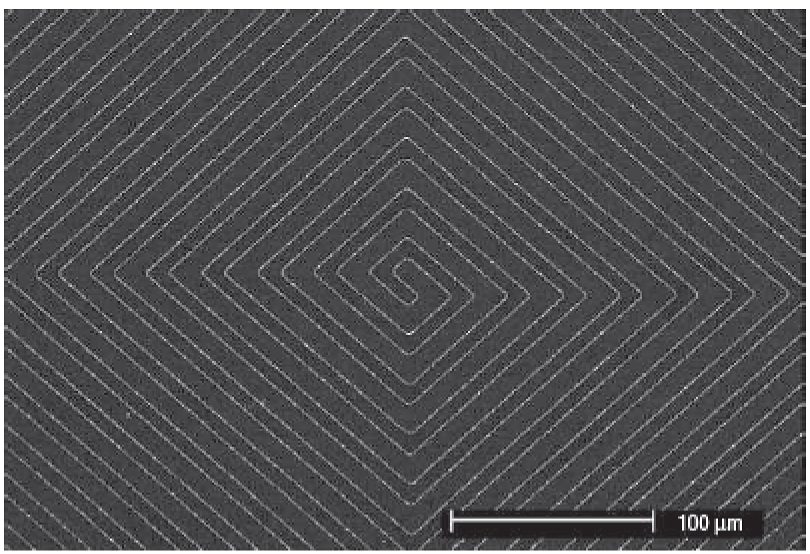
Figure 1 Seven-step process flow for metal-nanowire fabrication using LPNE.

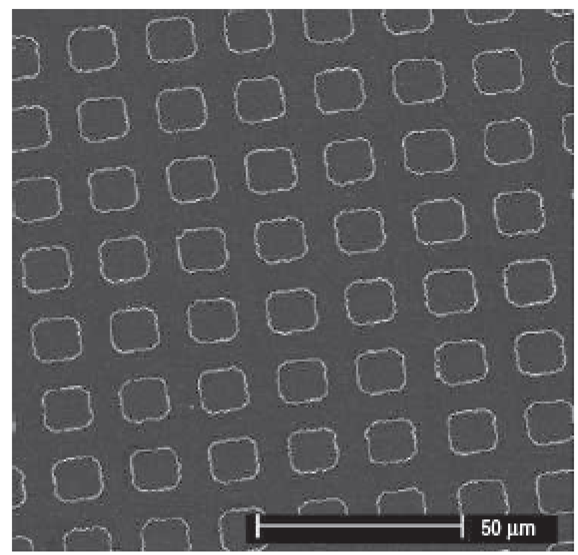
Figure 6 **A high degree of wire uniformity results in nanowires that are electrically continuous for up to 1.0 cm. a,** Current-versus-voltage curves acquired using four evaporated electrodes (inset). Data for two gold nanowires

real wires



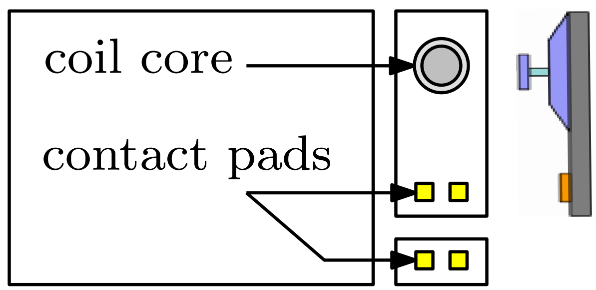




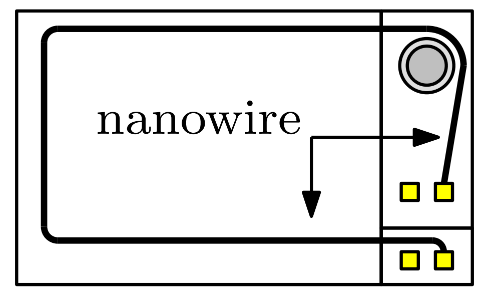


real coils? possibly

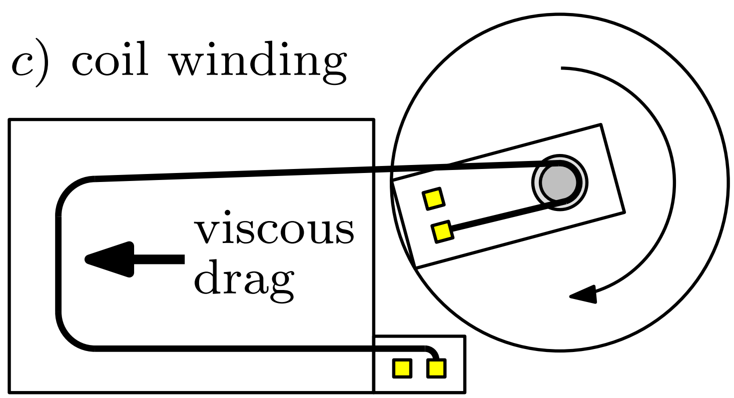
a) independent substrates



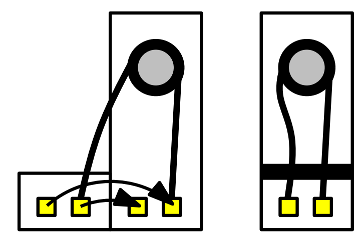
b) joint substrates



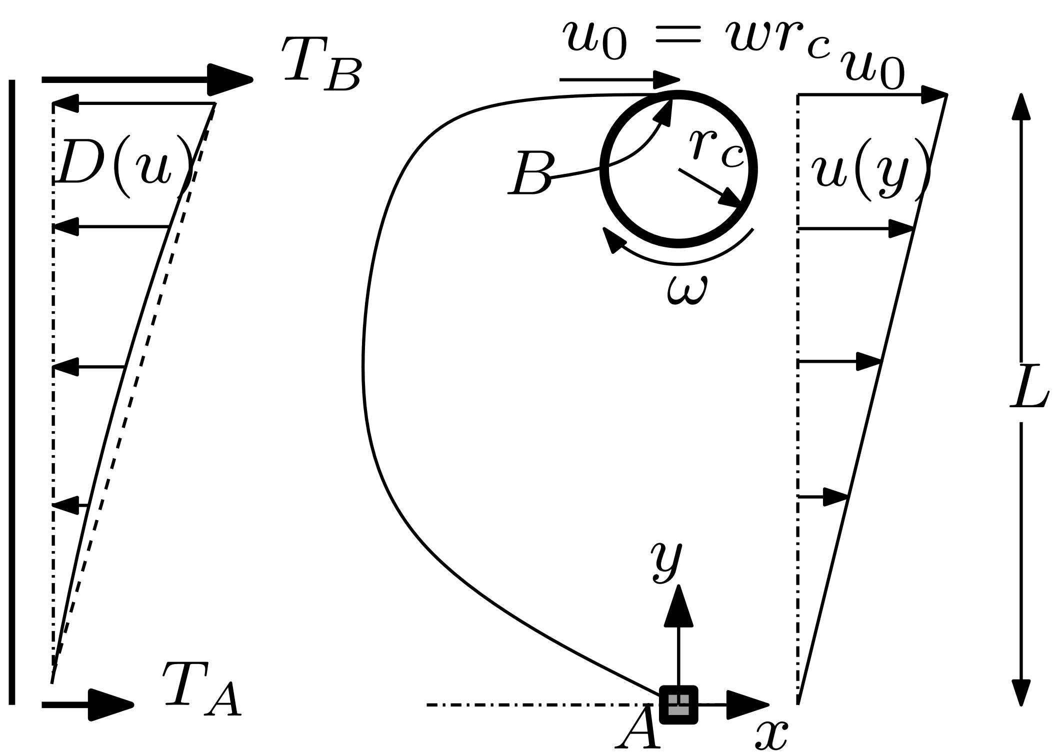
c) coil winding



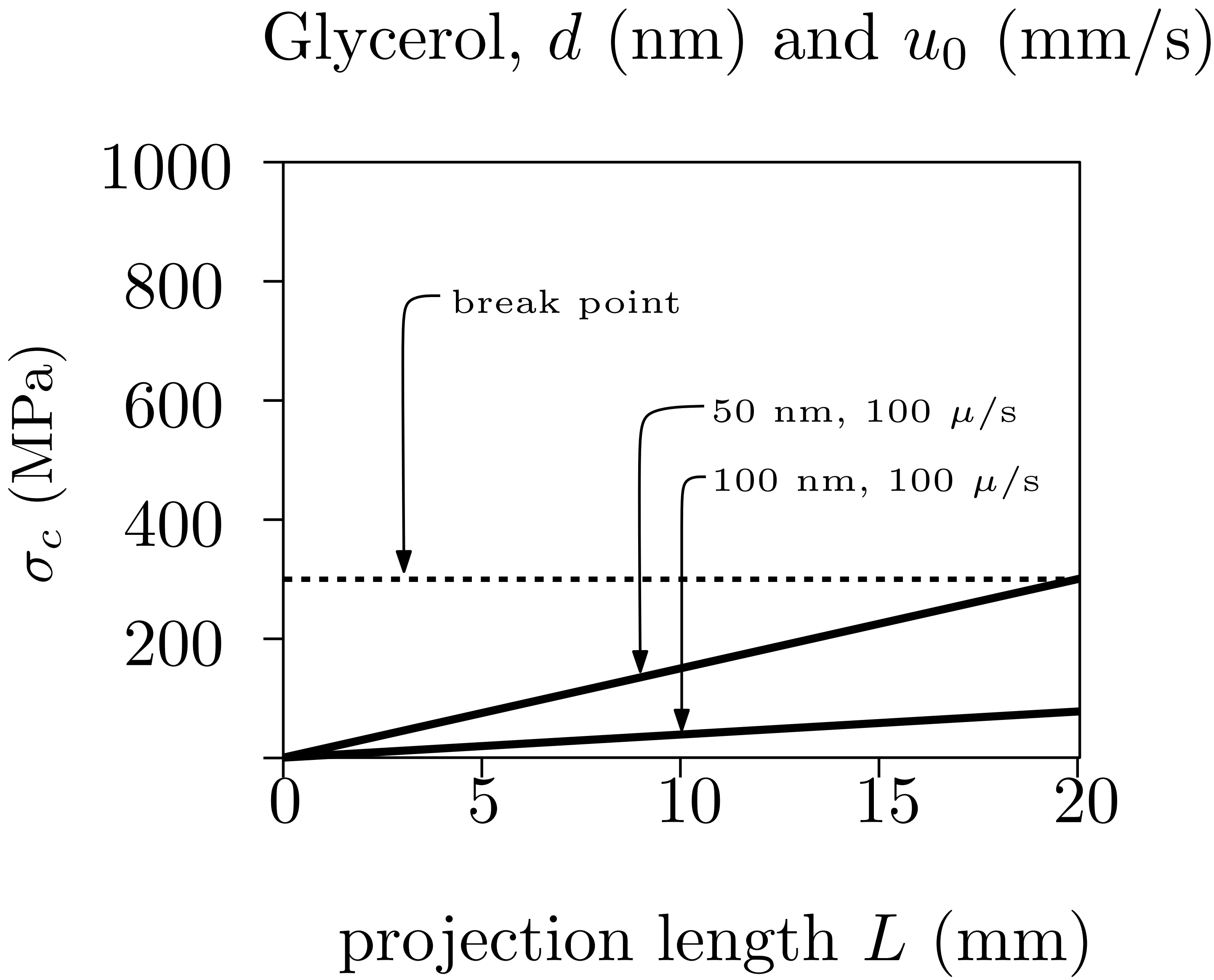
d) flip chip



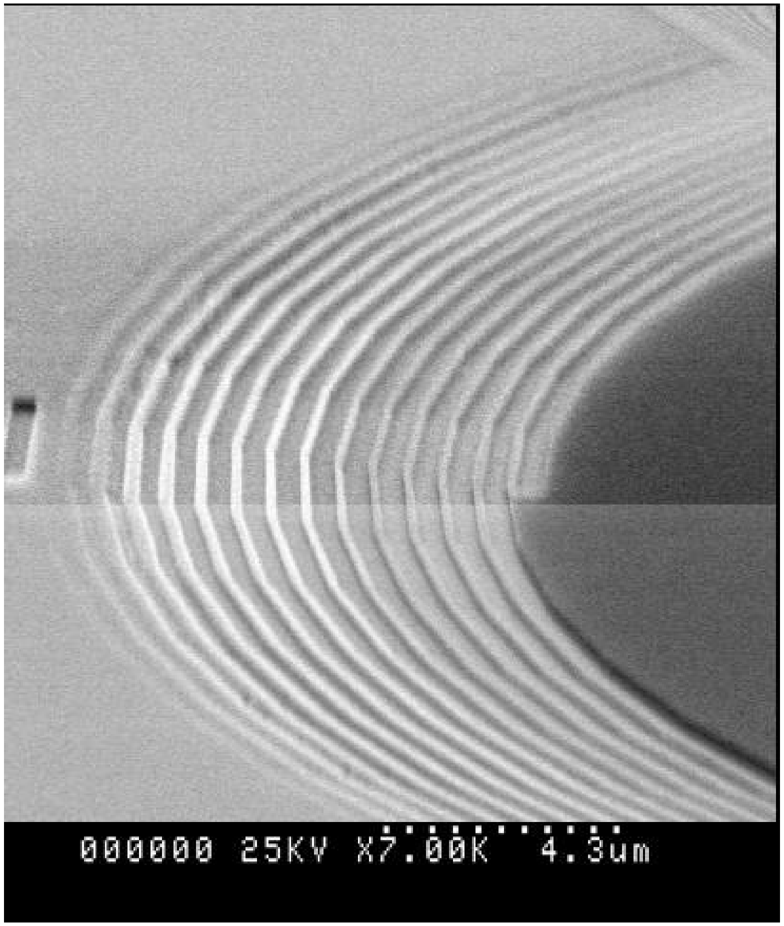
how fragile are the nanowires?



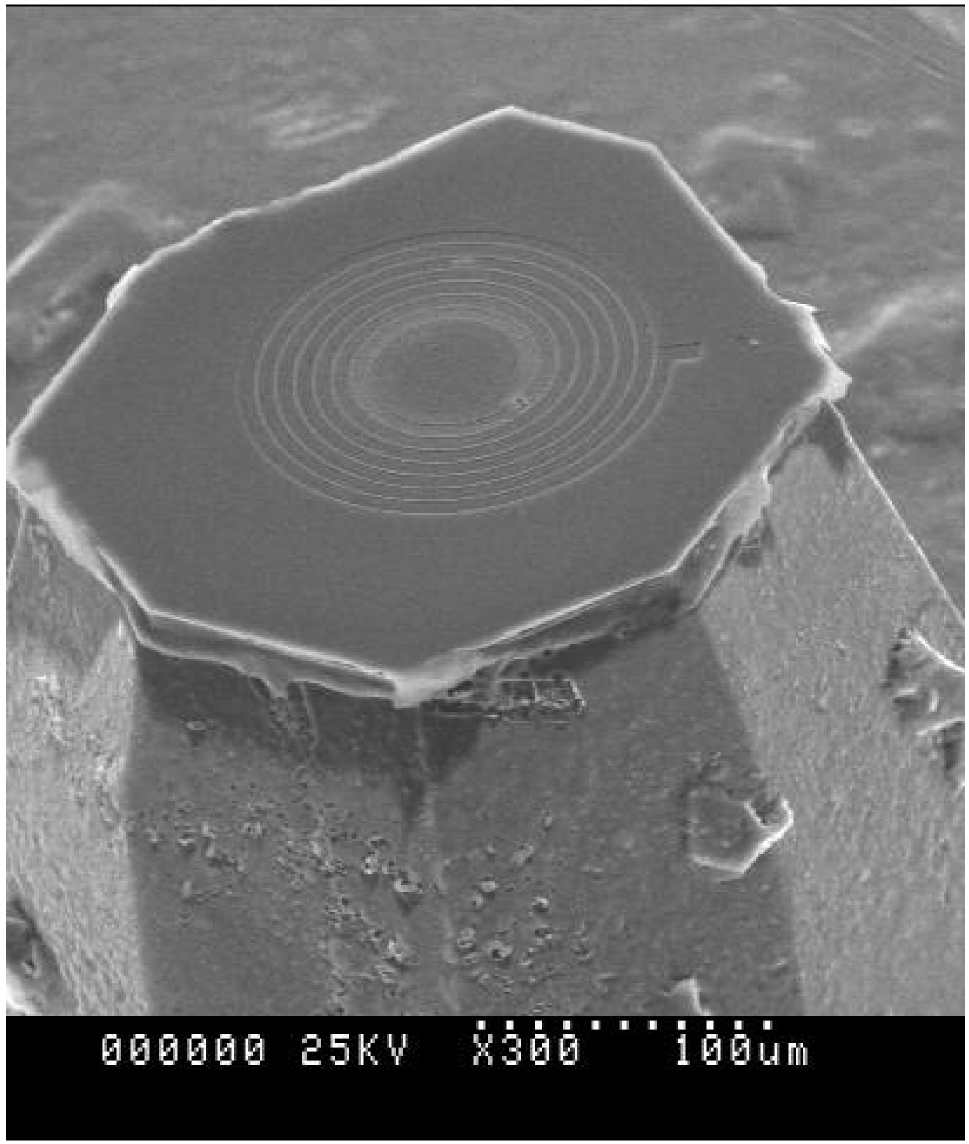
$$\sigma_c = \frac{16}{3d^2}\left\{\frac{\mu u_0 L}{2.002 - \ln(\frac{\rho}{\mu} u_0 d)}\right\} \text{ at point } B$$


Glycerol, d (nm) and u_0 (mm/s)
break point
50 nm, 100 μ/s
100 nm, 100 μ/s
1000
800
600
400
200
0
5
10
15
20
σ_c (MPa)
projection length L (mm)

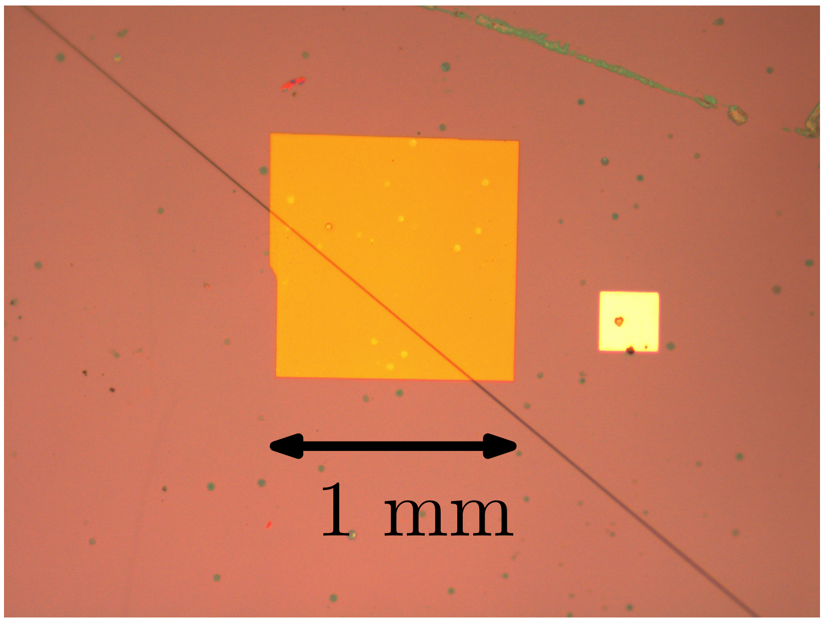
another technique, planar coils

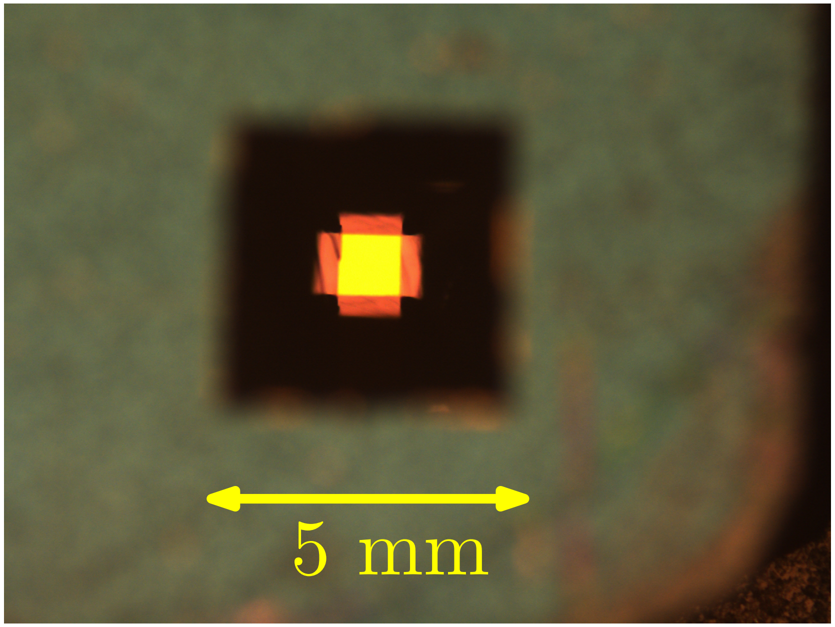


planar coils

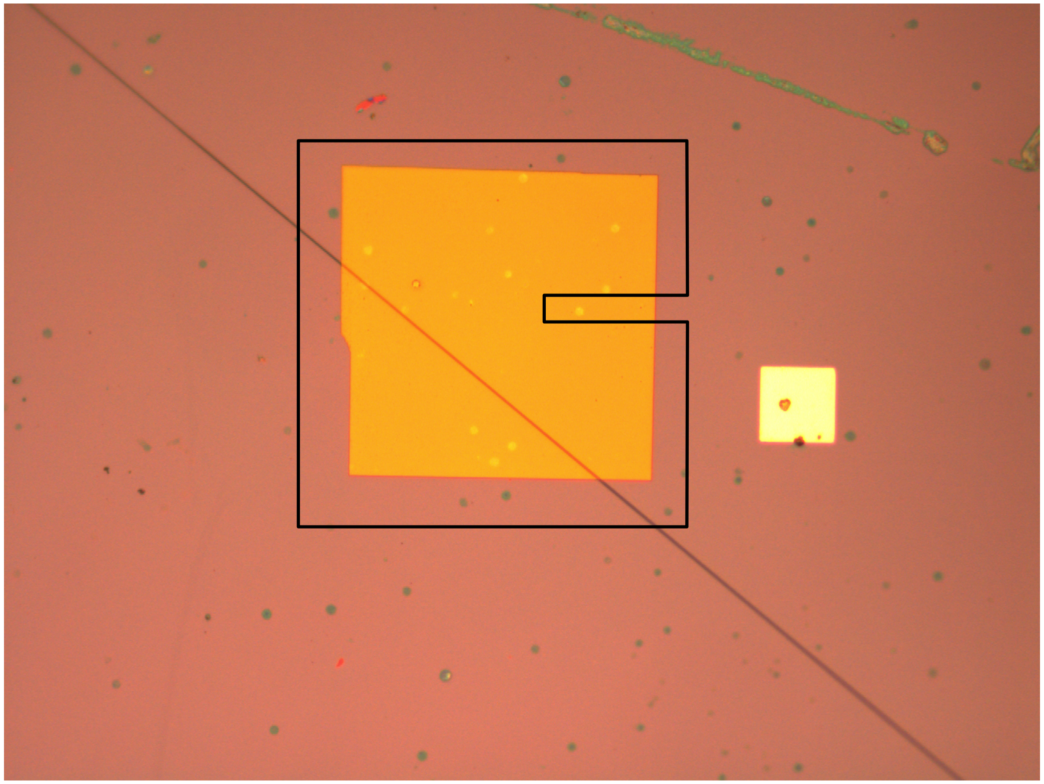


cantilever making

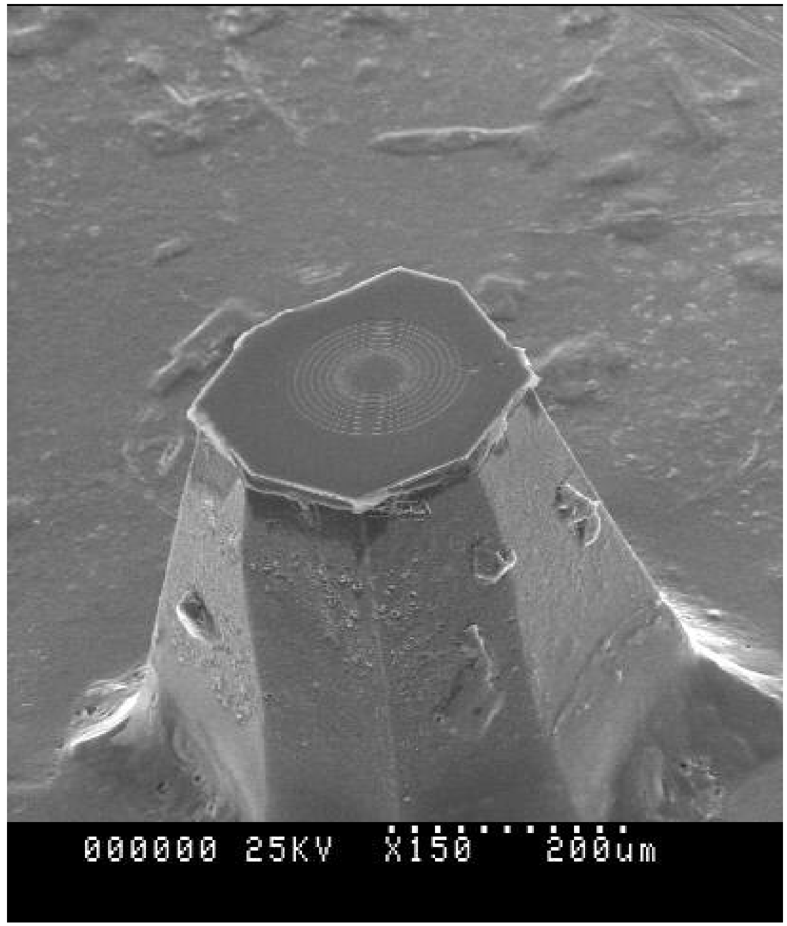




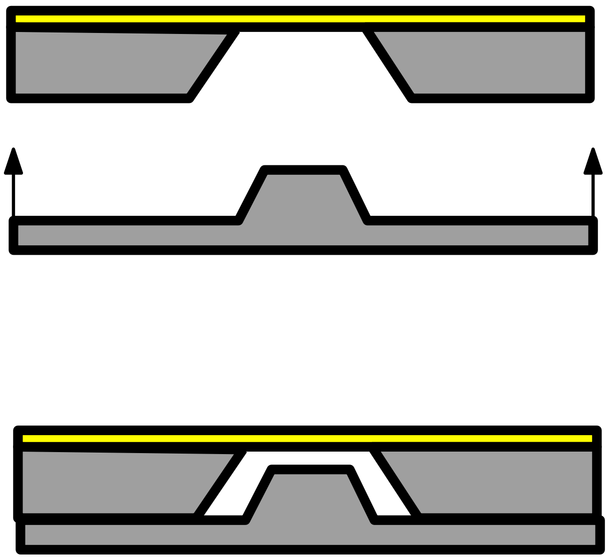
cantilever making

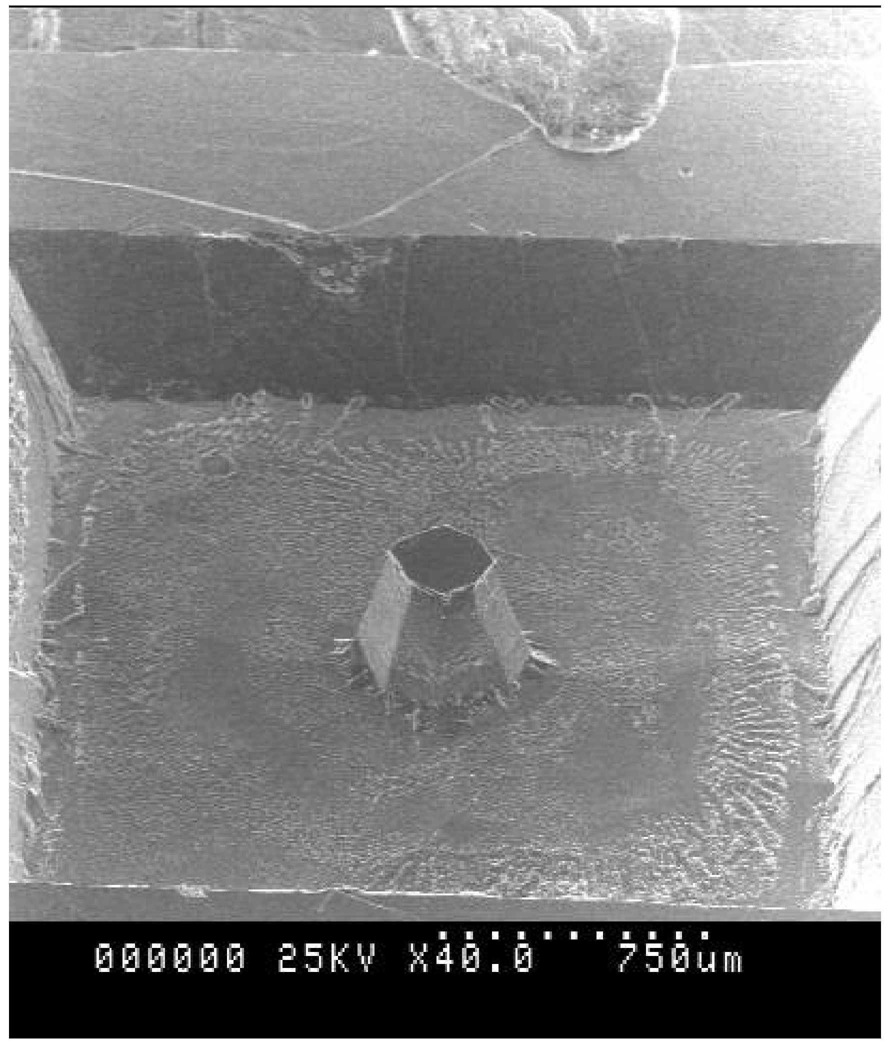


placing the coil

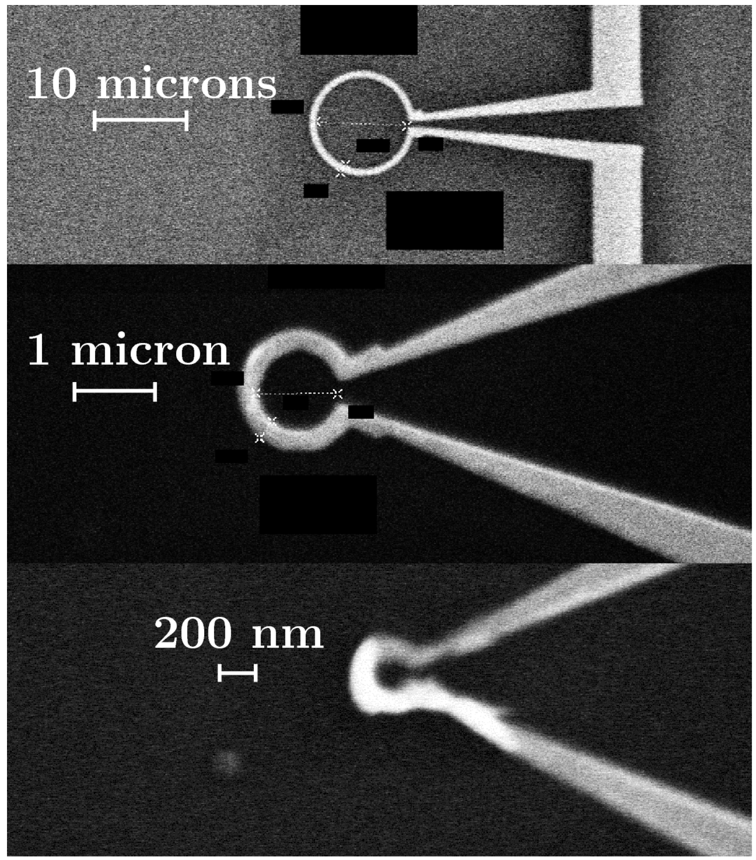


device packaging





epilogue



single loops. Gold over Cr/Si

to be continued ...

conclusions

For point source magnetic monents, the expected measured EMF should be 2 orders of magnitude larger than the intrinsic noise

Signal strength and intrinsic noise could be controlled by independent parameters (geometry and temperature, for instance)

thanks !