Driving a Macroscopic Oscillator with the Stochastic Motion of Hydrogen Molecule

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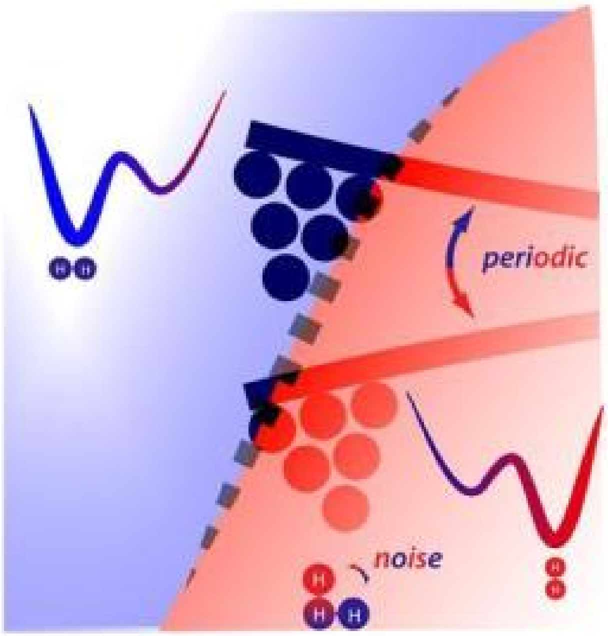
Transforming `Noise´ Into Mechanical Energy



Duygu Kantar

Mai 16, 2013

Structure

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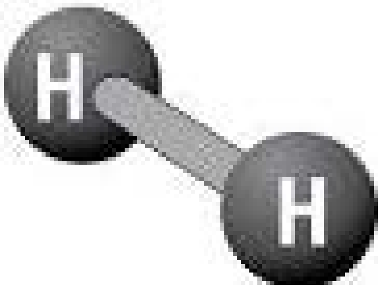
I. Motivation

- A single hydrogen molecule has been used to push an object much more massive than itself.



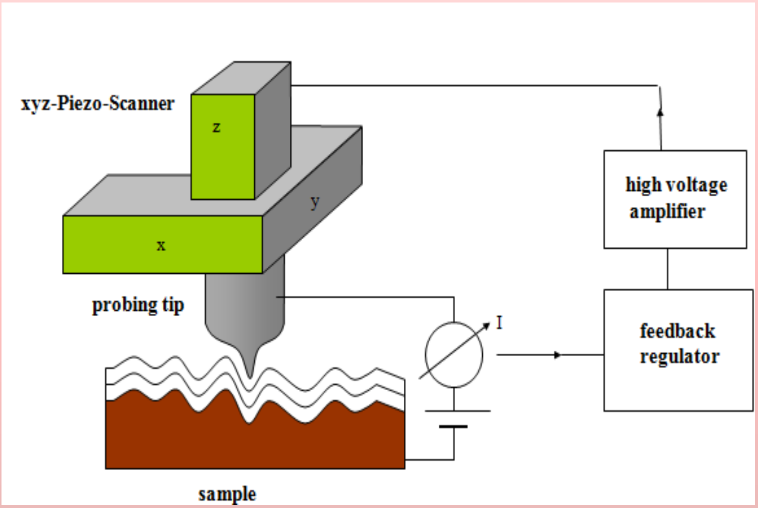
- Stochastic Resonance → tunneling electrons

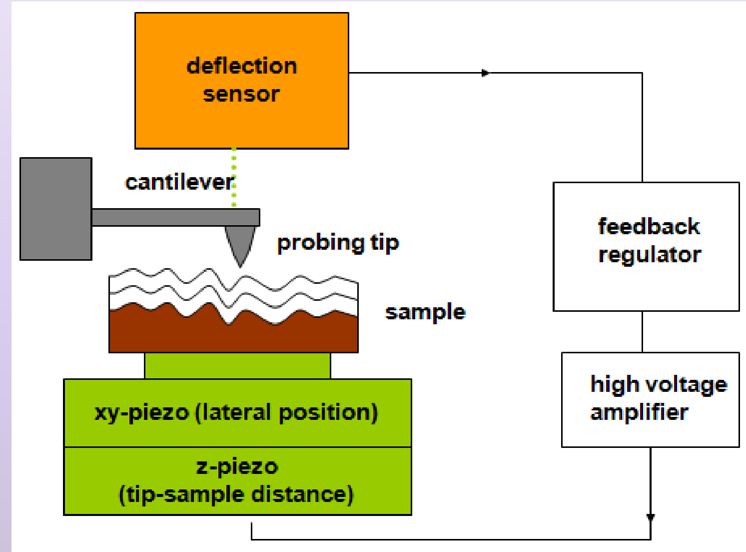
II. Materials and methods

- UHV
- Low temperature
- Single crystal Cu (111) sample as substrate
- STM equipped with a qPLus Sensor (LT-STM/AFM-System)

Picture : CreaTec Fischer & Co. GmbH

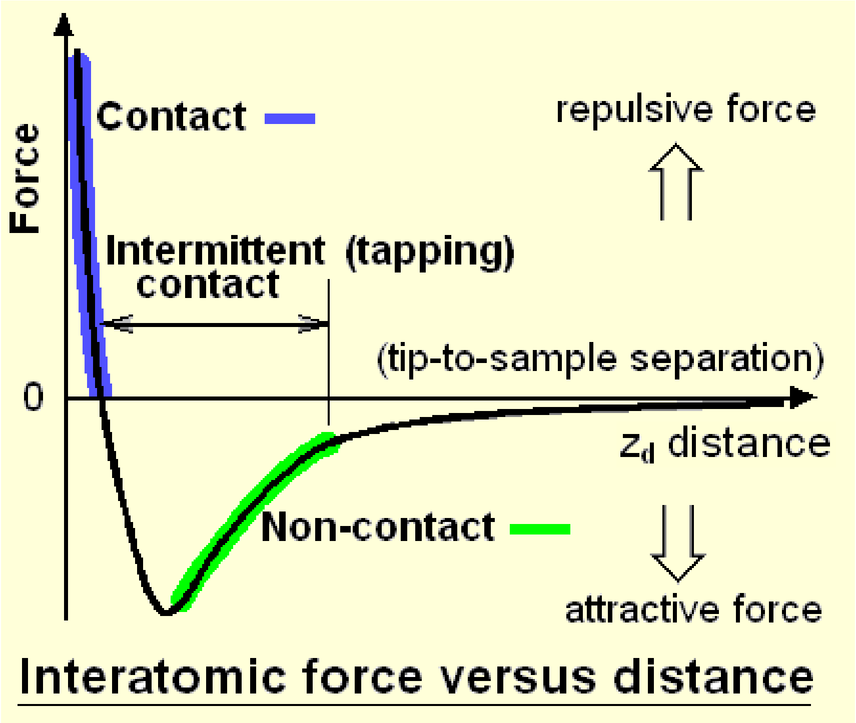
STM versus AFM





STM	AFM
• uses a sharpened conducting tip	• uses a conductive AFM cantilever with sharp tip at its end specimen surface
• relies on electrical current between the tip and the surface	• relies on movement due to the electromagnetic forces between atoms
• record the tunneling current	• record the small force between the tip and the surface
• applicable to conductors	• applicable to both conductors and insulators
• operates only in high vacuum	• suits well with liquid and gas environments

Non Contact AFM (frequency Modulation)



- **<u>Non-contact (NC) mode</u>:**

•Frequency modulation mode

•Constant amplitude maintained by separate feedback loop – can measure *dissipation*.

•Small changes in resonant frequency due to tip-sample interaction.

• Feedback loop causes tip to move over line of constant frequency shift.

Ampere A. Tseng 2010

Tuning Fork STM/nc-AFM

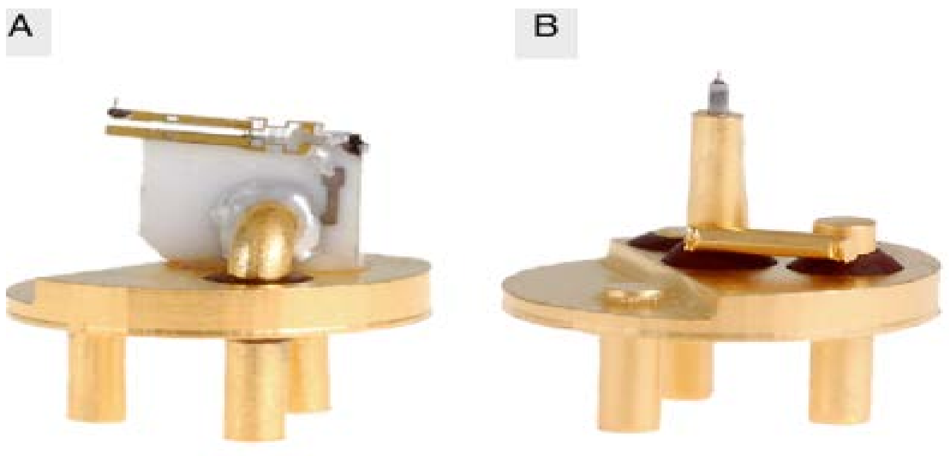
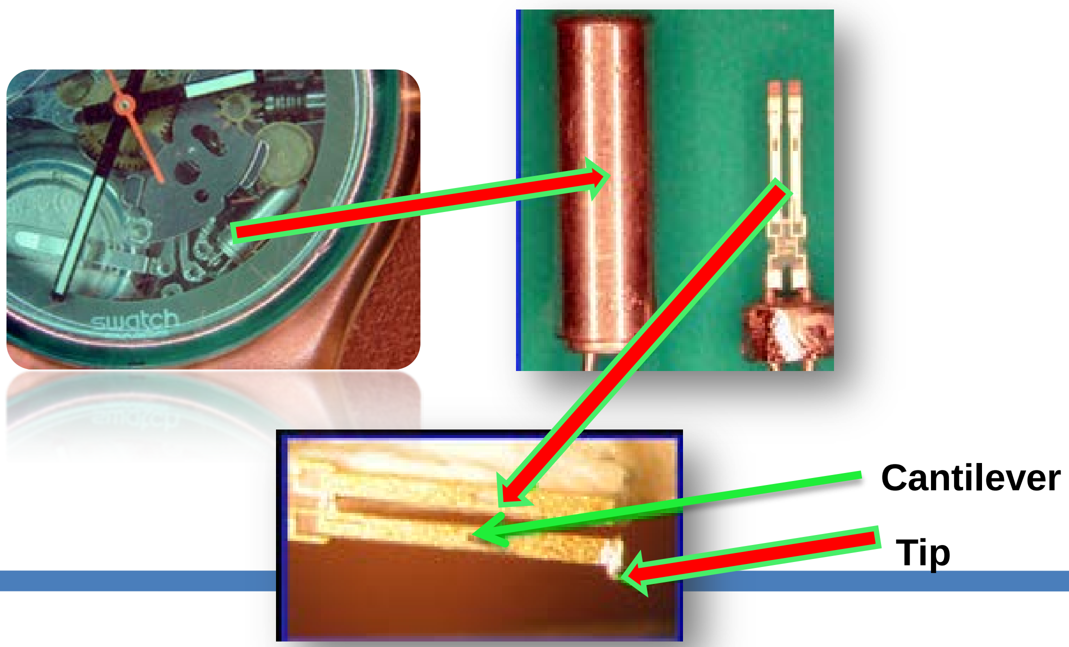


Fig.1. Pictures of a QPlus sensor (a) an STM tip (b) mounted on the LT STM sensor carrier. The stm tip is attached to the free prong of a tuning fork.



- Very small oscillation amplitude of STM tip: $A_{osc} < 0.5$ Å possible
- High stiffness: k=1800 N/m
- STM and nc-AFM measurement simultaneously

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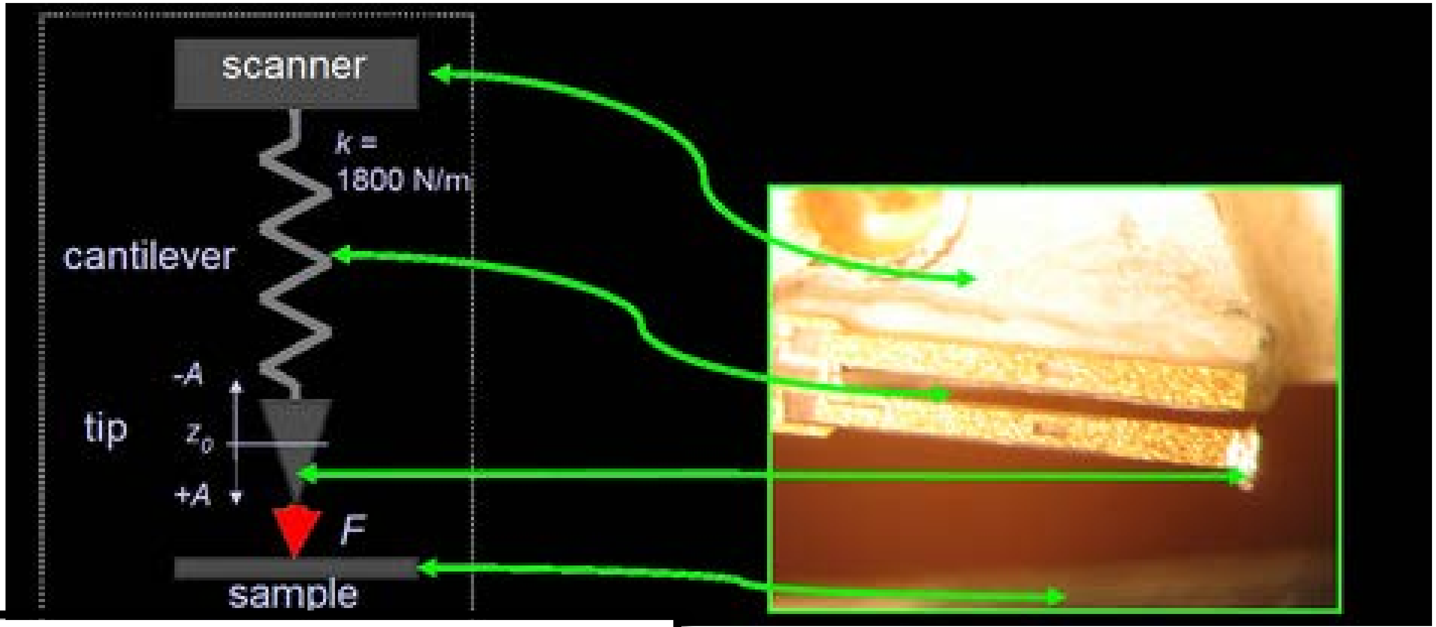


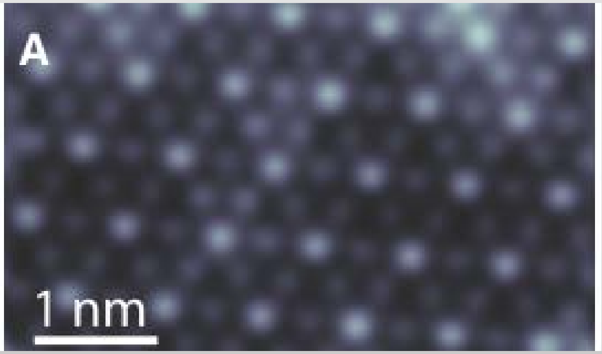
$$m\ddot{z} + kz + \frac{m\omega_0}{Q}\dot{z} = F_{ts} + F_0\cos(\omega t)$$

z is the displacement of the cantilever tip from its unperturbed position, **m** is the effective mass of the cantilever, **F_{ts}** is the interaction force between the tip and sample, **F_o** and **ω** are the amplitude and angular frequency of the driving force that excites the cantilever; **k**, **Q** and **ω_o** are the spring constant, quality factor, and angular resonance frequency of the cantilever in the absence of an interaction force, respectively.

If the tip-sample interaction force, F_{ts}, is not zero, the total force acting on the tip at the equilibrium position becomes, $F = F_{ts} - kz$

$$\left(\frac{dF}{dz}\right)_{z_0} = \left(\frac{dF_{ts}}{dz}\right)_{z_o} - k$$

III. Results



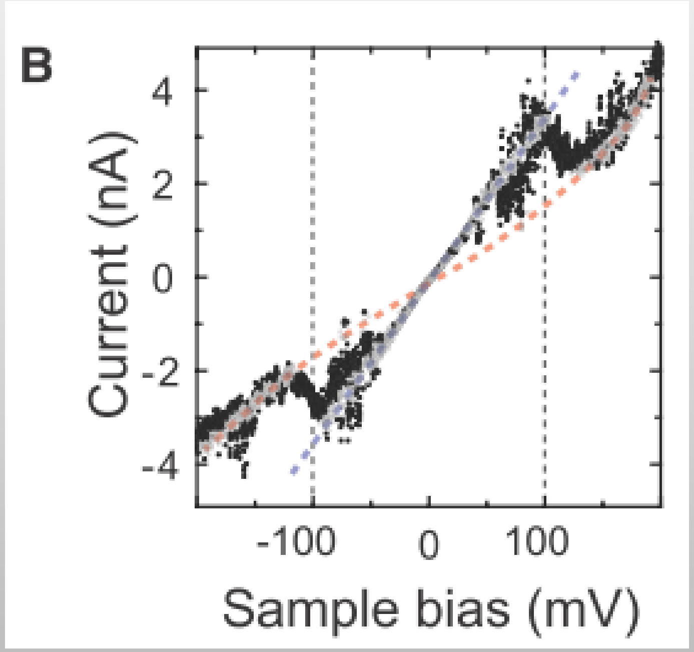


Fig.2. (**A**) STM image of a hexagonal H_2 layer on Cu(111) (V_S = -37 mV, I_t = 200pV. **(B)** Tunneling current

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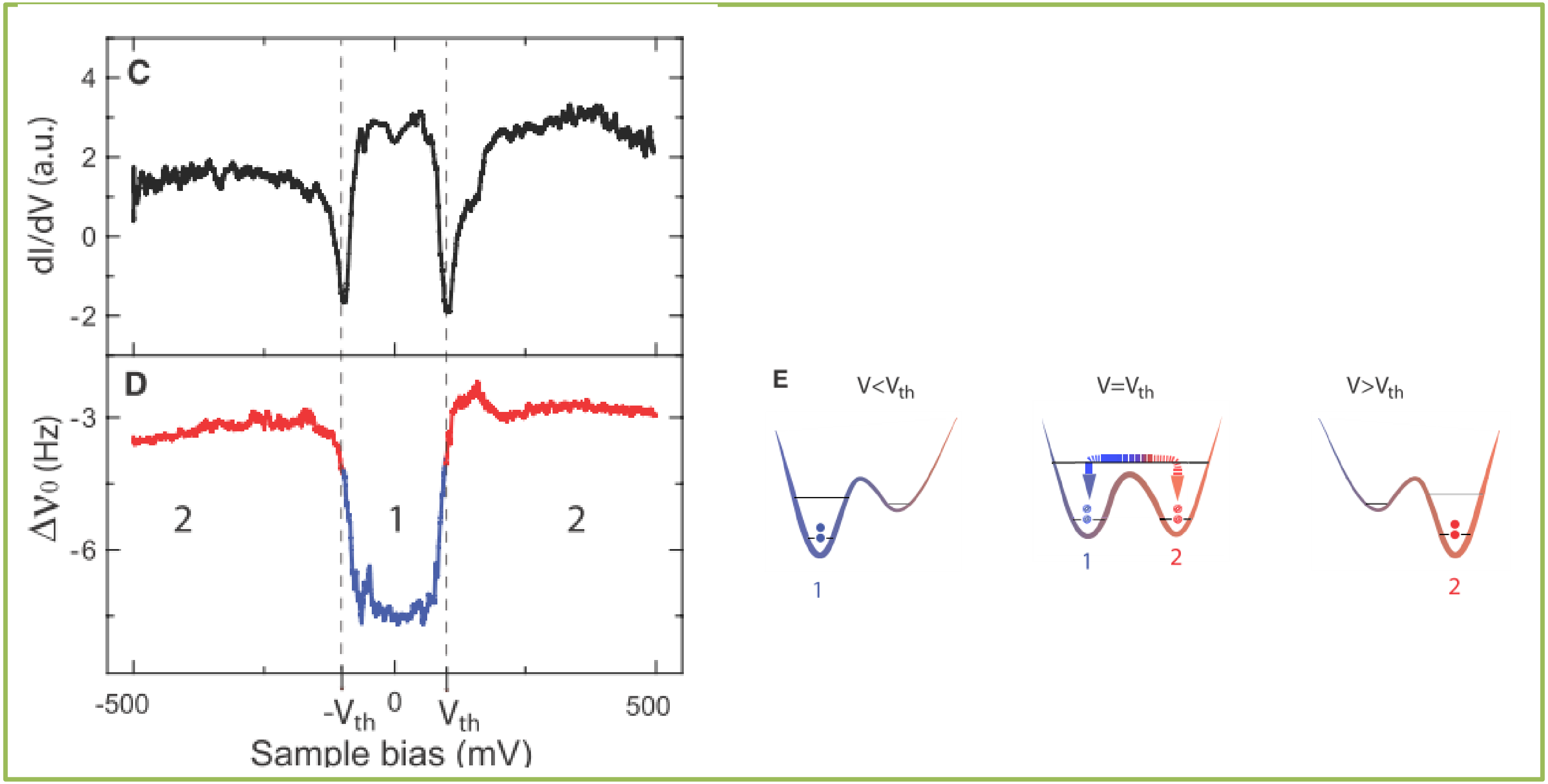

Fig.3. (**C**) differential conductance spectra of a Cu(111) surface with submonolayer H_2 coverage. The current spectrum shows two conductance regimes (marked with dashed lines) and an increased noise in the transition biases between them, at V_{th} ~ ±100 mV. The dI_t/dV_s spectrum shows dips with negative differential conductance at $\pm V_{th}$, caused by vibrationally induced fluctuations of a H_2 molecule between two configurations in the junction. (**D**) Simultaneously acquired plots of the frequency shift of the qPlus force sensor (A_{osc} = 50 pm, ν_0 = 20.609 kHz) reveal that the two states interact differently with the STM tip above and below V_{th}. (**E**) Model of the bistable potential and vibrational TLFs of a H_2 molecule in the tunnel junction.

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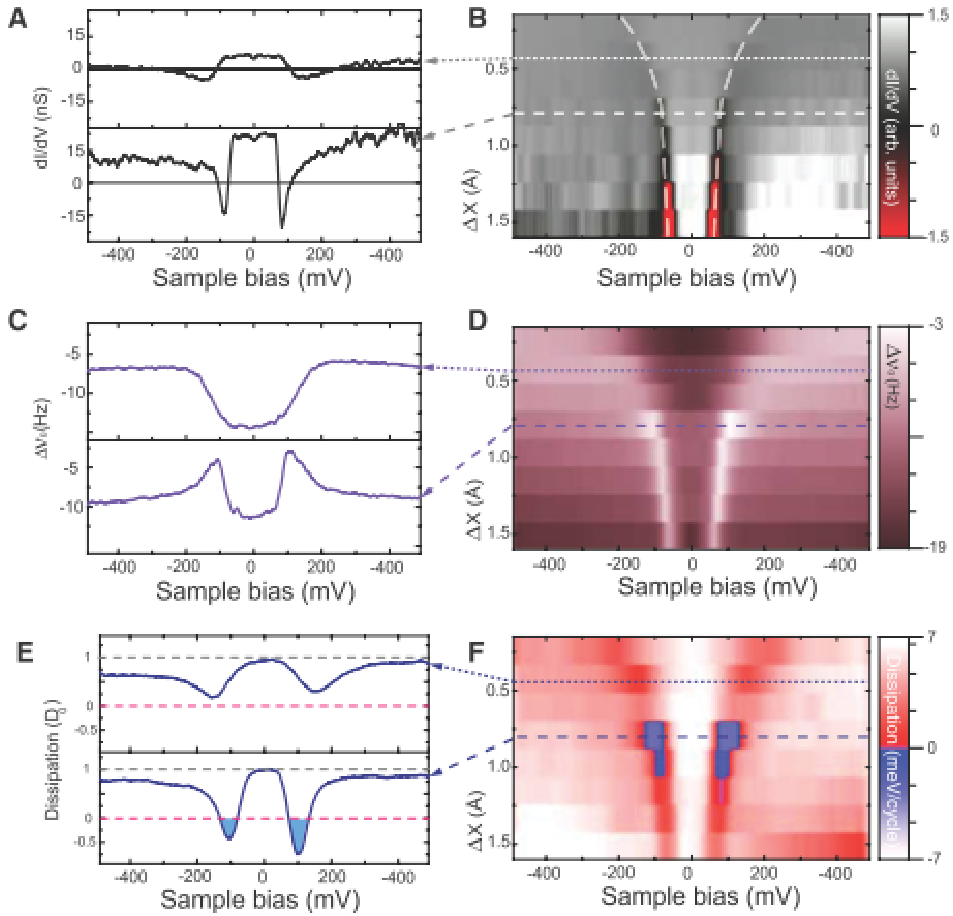

Fig.4. Simultaneously acquired spectra of the (**A** and **B**) differential conductance, (**C** and **D**) frequency shift, and (**E** and **F**) dissipation signal of a H_2 molecular junction at eight different tip-sample distances ($A_{osc} = 50$ pm, $\nu_0 = 20.609$ kHz). The color maps picture the corresponding magnitude versus bias and approaching distance ΔX with respect to an initial position with tunneling conductance 5 nS. The curved dashed lines in Fig. 2B indicate the reduction in the bias V_{th} with the tip-sample distance. The energy dissipation is plotted in units of D_0, the intrinsic dissipation of the free tip oscillating with $A_{osc} = 50$ pm (here, $D_0 = 7$ meV/cycle) [section 1.2 in (*10*)].

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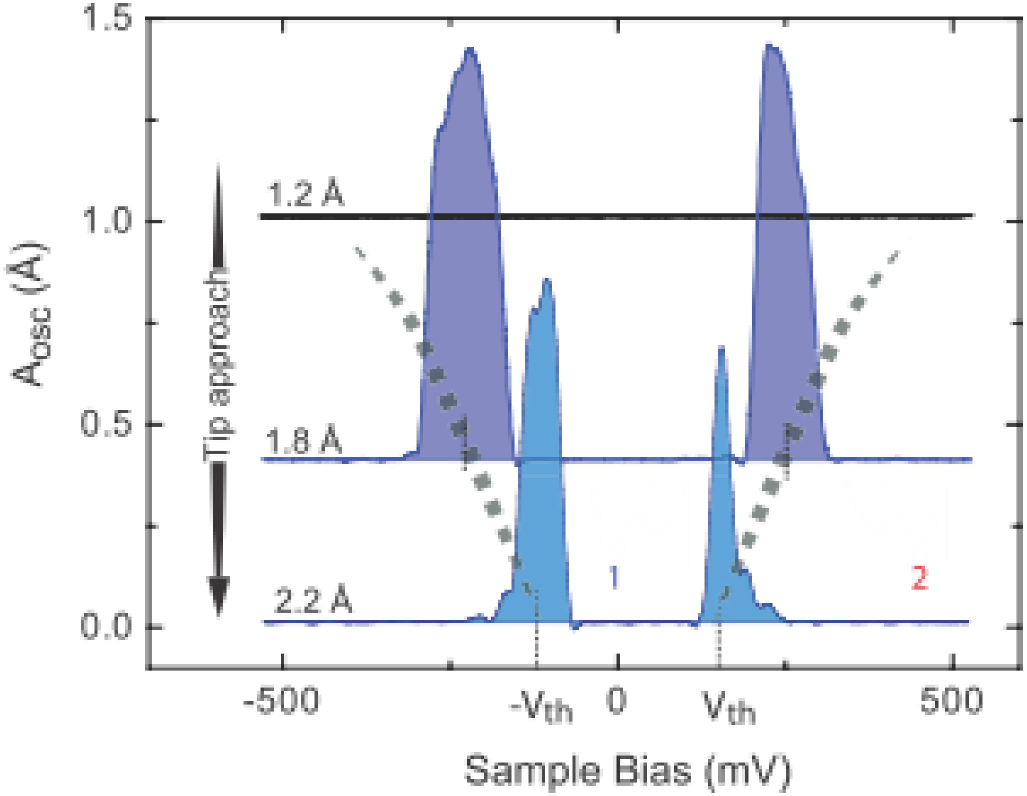
Fig.5 Oscillation amplitude A_{osc} versus sample bias in the absence of external driving forces (A_D = 0 mV). Each spectrum is measured at the indicated approach distances with respect to an initial position at junction conductance of 0.22 nS and shifted to lower values for clarity. The tip oscillates driven by electron-induced fluctuations of the H_2 molecule at $\pm V_{th}$. The dashed lines indicate the gradual decrease of V_{th} with the tip-sample distance.



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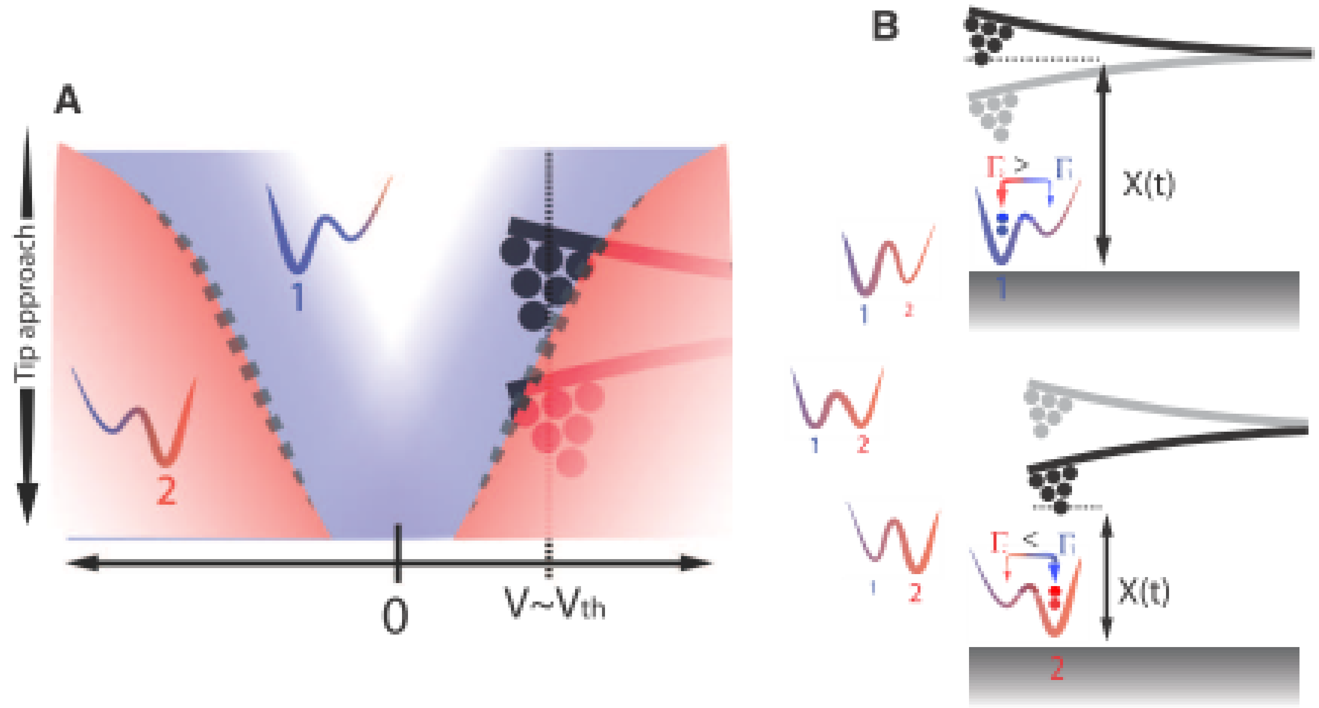

Fig.6. Sketch of the concerted dynamics of H_2 molecule fluctuations and tip periodic motion. (**A**) Bias-distance diagram of the population of the two states of H_2, summarizing the behavior depicted in Fig. 2. The tip oscillation at a bias V_{th} drives the system from the more attractive state 1 to the more repulsive state 2. (**B**) Diagram illustrating the tuning of the bistable potential of the H_2 molecule by the tip oscillation. When the tip is close (far) the state 2 (state 1) is more stable, and the rate Γ_2 (Γ_1) describing the switching out of state 2 (state 1) is smaller. The switching rates Γ_2 and Γ_1 have the opposite behavior with tip distance $X(t)$. The molecular conformation of the two states is unknown, albeit the vibration connecting them behaves as a frustrated H_2 rotation (*18*).

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IV. Conclusion

The noise of the molecule is made by injecting electric current, not temperature, through the molecule and thus, functions like an engine converting electric energy into mechanical.

V. Literature

1. Christian Lotze et al. *Science* 338,779 (2012)
2. Materials and methods are availavle as supplementary materials on *Science* online
3. Appl. Phys. Lett. 76, 1470 (2000)
4. Luca Gammaitoni et al. Rev. Mod. Phys., Vol. 70, No. 1, January 1998
5. Jan Iwaniszewski, Phys. Rev. E 61, 4890 (2000)
6. W.H.A. Thijssen, D. Djukic, A.F. Otte, R.H. Bremmer, J.M. van Ruitenbeek, 10.1103/PhysRevLett.97.226806

Thank You for your attention!!