All-Optical Super-resolution Quantum Thermometry with Individual Two-Level-Systems

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Understanding and controlling heat at the nanoscale is essential for the operation of novel quantum devices, where local dissipation can strongly affect coherence and stability. Here we introduce an all-optical temperature sensor that detects sub-millikelvin thermal variations with ~10 nanometer spatial resolution.

The sensor is based on individual atomic-scale naturally-occurring two-level systems (TLSs) that are dispersively coupled to a single organic molecule [1] within a nanoprinted host crystal [2]. This coupling enables optical readout of the TLS state and, therefore, its temporal dynamics. We show that the TLS transition rates depend exponentially on their local temperature, providing exceptional sensitivity of around 6 mK/Hz$^{1/2}$ at 2 K. We then use this high locality and sensitivity to detect heat produced by other nearby molecules, demonstrating the local effective temperature rise of up to 40 mK at a distance of 100 nm [3].

The demonstrated spatial resolution and temperature sensitivity, together with the flexibility of nanoprinting for placing molecule on various substrates, provides a promising platform for local temperature measurements on quantum devices operating below 5 Kelvin.

References

[1] Toninelli, C. *et al*. *Nat. Mater.* 12 (2021) 1615-1628
[2] Musavinezhad, M. *et al. ACS Nano*, 33 (2024) 21886–21893
[3] Musavinezhad, M. *et al.* in preparation.

Figures

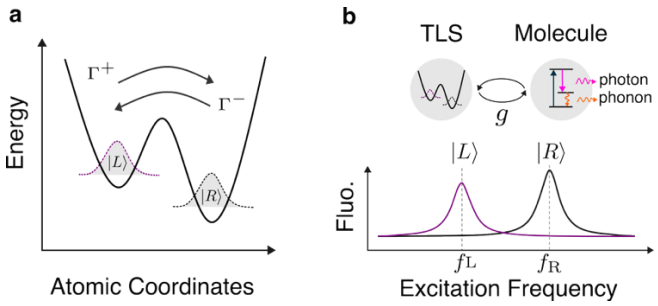

Figure 1: (a) Potential landscape of a single TLS. Transition rates $\Gamma^{\pm}$ between the two states depend on the barrier height and temperature. (b, top) Schematics of a TLS strongly coupled to a molecule. (b, bottom) Optical resonance of the molecule shifts depending on the TLS state, allowing for optical readout of the TLS dynamics.

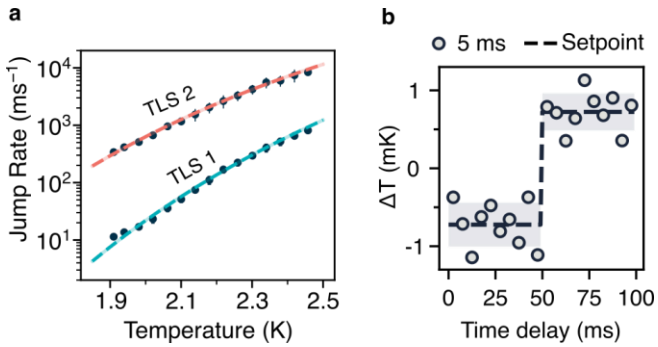

Figure 2: (a) Jump rates of two independent TLSs as a function of temperature. Curves are fits to the Arrhenius activation law. (b) Time-resolved temperature measurement for a laser spot locally heating the sample by 1.4(4) mK. Time resolution is 5 ms. The data is accumulated over about 2x10^5 repetitions.