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An RF Photon-Number-Resolving Detector Using Majorana Zero Mode



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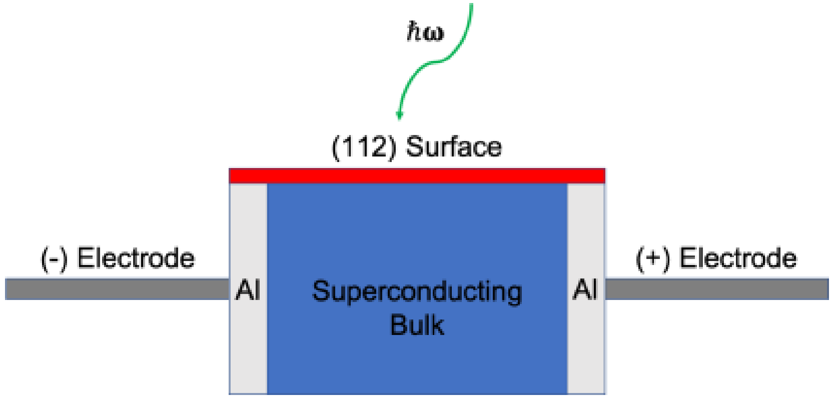
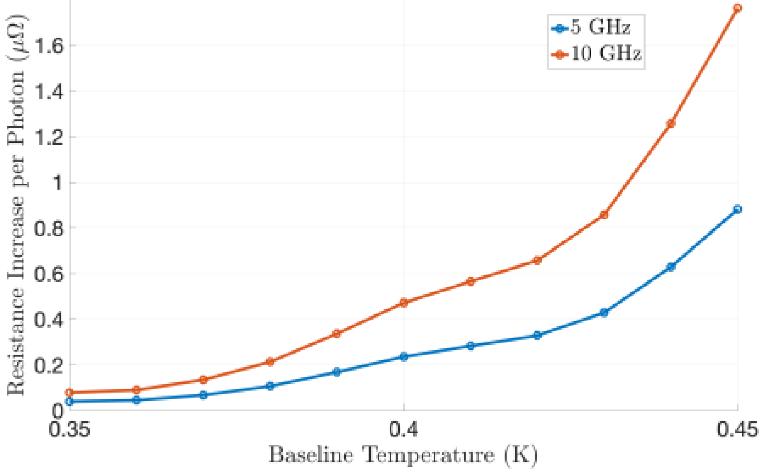
The need for RF photon number detectors

- RF photon number detectors essential in transmon-based quantum computing
  - Especially important: detecting photons in transmon frequency range ~5-7 GHz
- How they work: electrons absorbs incoming photons, and then transfers energy (as heat) to lattice vibration, raising temperature
- Detect temperature gain by dynamically measuring transverse resistance
- Need to satisfy the following criteria:
  - Establish spatial separation between absorber and bolometer, so that excited photoelectron is not washed out by the dynamic resistance measurement
  - Guarantee that heat transfer from absorber to bolometer is much faster than parasitic photoelectron loss processes (e.g., radiative decay)
  - Ensure that the temperature gain per photon is high enough to be easily resolvable

Building on Our Recent Work

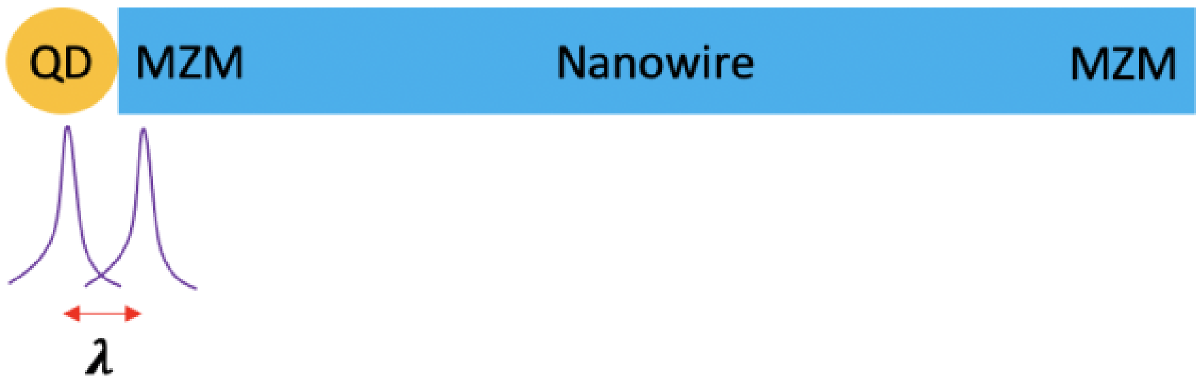
- Recently, we pioneered microwave photon number detector using topological semimetal cadmium arsenide (Chatterjee *et al.*, *Phys. Rev. Research* **3**, 023046 (2021))
  - At low temperature (< 0.7 K): Bulk becomes superconducting, while surface state remains semimetallic (graphene-like electron dispersion)
  - Superconducting gap is significantly larger than photon frequency
  - Surface electrons absorb incoming photons, and then transfer heat to bulk phonons (lattice vibrations), raising the bulk temperature
- Satisfies spatial separation between absorber (surface) and bolometer (bulk), as well as rapid heat transfer from absorber to bolometer, but:
  - **Problem:** Temperature gain (and hence resistance gain) per photon is too small for true single-photon detection resolution



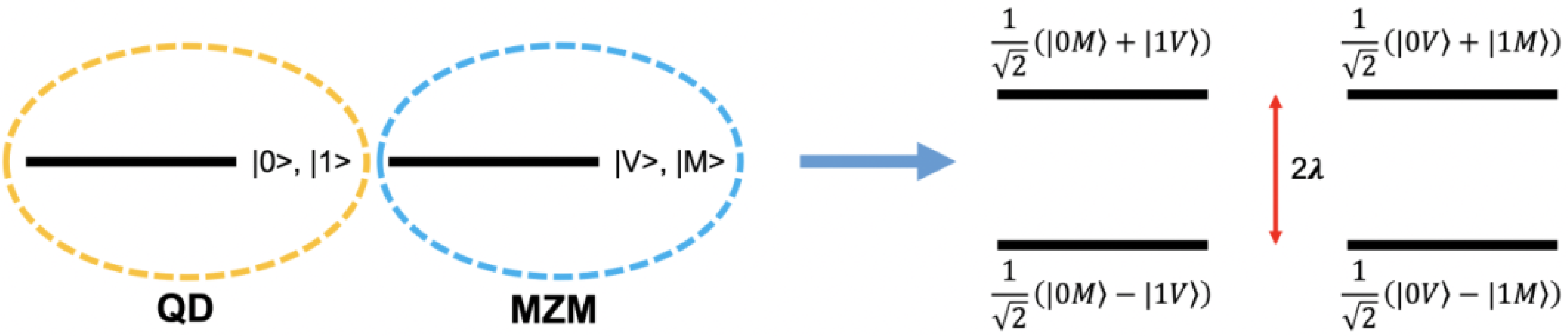


Physical Setup

- **Key idea:** Use low-dimensional system (0D absorber, 1D bolometer)
  - Far lower heat capacity, and thus much higher temperature gain per absorbed photon
- *p*-wave superconducting nanowires are theorized to host localized Majorana zero mode (MZM) at each edge
- **Problem:** MZM is chargeless and gapless, and thus cannot absorb photons by itself
- **Solution:** Side-couple MZM to quantum dot (QD)
  - QD-MZM charge-carrier hopping leads to hybridized states separated by microwave-frequency gap



Physical Setup (Cont.)



- Physical interpretation of hybridization:
  - $|0M\rangle \leftrightarrow |1V\rangle$: Electron hops between QD and MZM modes
  - $|1M\rangle \leftrightarrow |0V\rangle$: Hole hops between QD and MZM modes
- Tune QD-MZM hopping strength λ so that gap 2λ is resonant with photons ($\omega = 2\lambda$)
  - Gap is much smaller than superconducting gap in nanowire bulk
- Photoelectron decays through energy transfer to nanowire bulk phonons
  - Need to show that this rate is much faster than spontaneous photon emission
  - Detect temperature increase by dynamically measuring transverse bulk resistance

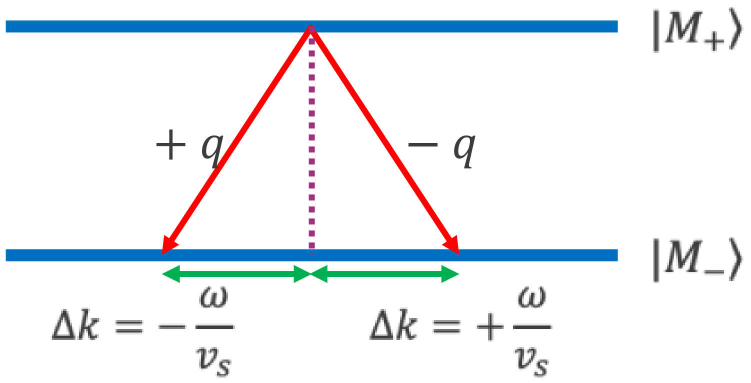
Calculating the Phonon Emission Rate

- Decompose Majorana edge state into superposition of 1D bulk plane waves

$$|M\rangle = \sqrt{\frac{a}{L}} \sum_{k=-\pi/a}^{\pi/a} |k\rangle \, .$$

a: Majorana coherence length
L: nanowire length

- Phonon emission couples Majorana parts of upper (+) and lower (-) hybridized states



- Long-wavelength acoustic phonons: Use deformation potential treatment to calculate electron-phonon matrix element

$$\sum_{\mu} |\hbar g_{\mu,q}|^2 = \frac{\hbar D^2}{2\rho v_s V} |q|$$

- Emission rate from Fermi's Golden Rule:

$$\Gamma_{\rm nr}(T) = \frac{D^2 \omega}{4\hbar \rho A v_s^3} \left(\left(e^{\frac{\hbar\omega}{k_B T}} - 1 \right)^{-1} + 1 \right)$$

D: deformation potential
ρ: nanowire density
v_s: speed of sound in nanowire
A: nanowire cross-sectional area

Deriving the Transition Dipole Moment

- Necessary for calculating the following:
  - Photon absorption rate (to determine required density of nanowires on-chip)
  - Photoelectron spontaneous photon emission rate (to compare to phonon emission rate)
- Majorana wavefunction exponentially decays away from nanowire edge
  - Coherence length ~ 14 nm (Chiu *et al.*, *Sci. Adv.* **6**, eaay0443 (2020))
  - Can effectively model nanowire edge potential as square well
- Steps for calculating transition dipole moment:
  - Model quantum dot as square well (analogous to nanowire edge)
  - Derive transition dipole moment as function of QD-nanowire distance l
  - Determine l corresponding to QD-MZM hopping strength $\boldsymbol{\lambda}$
- For large QD-nanowire separation, moment scales with MZM coherence length $1/\boldsymbol{\kappa}$
  - Intuition: For a smaller coherence length, QD needs to be moved closer to nanowire to achieve to same hopping strength, leading to smaller moment (and vice versa)

$$d_{+,-} = -\frac{q_e}{\sqrt{2}\kappa}\left(\frac{\kappa l}{\kappa l + 3}\right)$$

Numerical Results

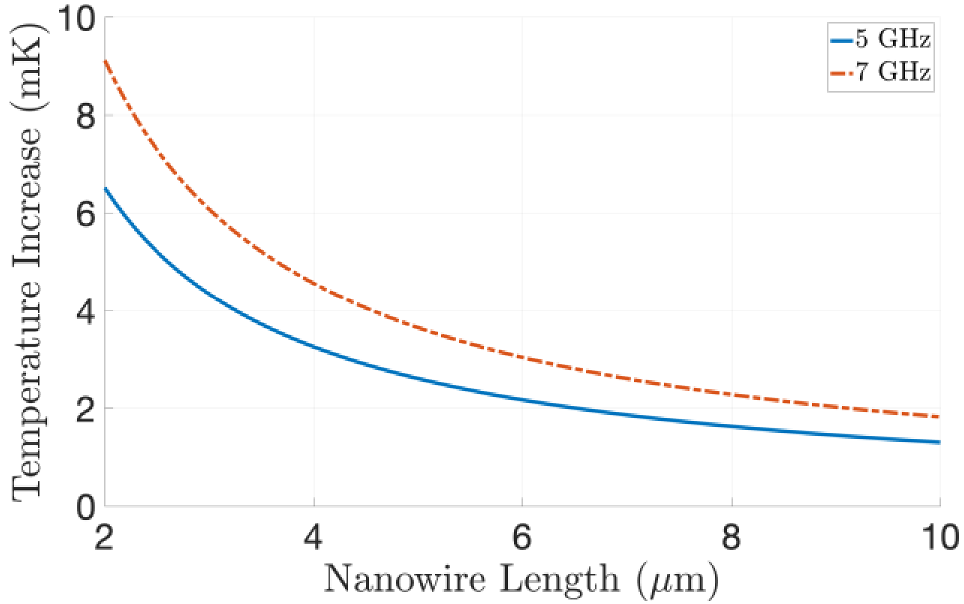
- For 5-GHz resonance frequency, QD-nanowire distance = 59 nm, yielding dipole moment amplitude = 9.3×10^{-28} C·m
  - Resulting spontaneous photon emission rate ~ 10^{-4} s^{-1}
- Optimal parameters:
  - InAs nanowire: high speed of sound leads to greater temperature gain per photon
  - Diameter ~ 20 nm
  - Minimum length ~ 1.4 μm (to ensure that length is 100x Majorana coherence length)
  - Baseline temperature ~ 0.2 K; use titanium (T_c ~ 0.4 K) to induce superconductivity
- Use Fermi's Golden Rule to calculate absorption rate per QD-nanowire complex
  - Rate becomes inversely proportional to beam area
  - Absorption rate reaches 98% for array of QD-nanowire complexes on-chip (unit cell dimensions: transverse ~ 100 nm, longitudinal ~ 2 μm) inside microwave cavity

Numerical Results (Cont.)

- Given these parameters, phonon emission rate ~ 6×10^8 s^{-1}
  - Far higher than spontaneous photon emission rate, as desired
- Determine nanowire heat capacity from phonon density of states $C_{ph}(T) = \frac{dU_{ph}}{dT} = \frac{\pi L k_B^2}{\hbar v_s} T.$
  - 1D system: heat capacity scales linearly with baseline temperature *T*
  - Temperature increase per photon becomes an inverse function of nanowire length

$$\Delta T = \left(4.1 \times 10^{-19}\ \mathrm{m \cdot s \cdot K}\right) \frac{\omega}{L}.$$

  - Single-photon temperature gain in mK range, far higher than nK range for Cd_3As_2



Conclusion

- We have devised a scheme for high-resolution microwave photon number detection at the single-photon level using an array of nanowires coupled to quantum dots
- Essential for transmon-based quantum computing
- See published result on Cd_3As_2 detector in Physical Review Research
- Paper on QD-nanowire detector coming soon

PHYSICAL REVIEW RESEARCH **3**, 023046 (2021)

Microwave photon number resolving detector using the topological surface state of superconducting cadmium arsenide

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