Supplementary Information: Demonstration of Distributed Capacitance Compensation in a Metal-Insulator-Metal Infrared Rectenna Incorporating a Traveling-Wave Diode

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Table I Support Calculations

From two separate simulations of the TWD structure by itself and the antenna by itself, we estimate the real part of TWD input impedance is 20 Ω and the imaginary part is 15 Ω. The antenna impedance is estimated to be 80 Ω real and -104 Ω imaginary. Using the antenna and TWD impedances, the coupling efficiency is calculated using the following equation:

$$\eta_c = \frac{4R_{twd}R_{ant}}{(R_{twd}+R_{ant})^2+(X_{twd}+X_{ant})^2} \tag{S1}$$

where R_{ant} and X_{ant} represent the real and imaginary parts of the antenna impedance, respectively. R_{twd} and X_{twd} are the real and imaginary parts of the TWD input impedance, respectively. Note, R_{twd} should not be confused with the diode DC resistance. When the simulated impedances for both the antenna and TWD are plugged into S1, the resulting estimated coupling efficiency between the TWD and the antenna is $\sim$ 35 %.

The coupling efficiency for a lumped-element rectenna is calculated using the same equation (S1), with one major difference. The TWD real and imaginary impedances are replaced with the series equivalent of the diode resistance, R_d in parallel with the impedance due to diode capacitance ($R_d||1/\mathrm{j}\omega C_d$). The capacitance of the diode, C_d, is calculated as the planar geometric capacitance ($\epsilon_0\epsilon_r A/d$) where ϵ_r is the effective relative dielectric constant of the insulators ($\sim$10), A is the MIM area (115 nm x 1350 nm), and d is the dielectric thickness (5 nm). The effective diode impedance is 0.01-0.005j Ω, which results in an estimated coupling efficiency of $\sim$0.02%.

We can use the following equation to estimate $I_{sc/LE}$, the short-circuit current from the lumped-element rectenna:

$$I_{sc/LE} = P_{in}\eta_{ant}\eta_c\beta_0 \tag{S2}$$

where η_{ant} is the maximum antenna absorption estimated to be ~10%, β_0 is the zero-bias responsivity, 0.46 A/W, calculated from the DC $I(V)$ fit. η_c, comes from supplementary material equation (S1) as calculated for the lumped-element above. When these values are plugged into supplementary material equation (S2), the result is $I_{sc/LE}$ is 0.23 nA.

The plasmonic loss can be estimated to be ~99% by looking at the difference between the estimated improvement in coupling efficiency between the antenna and diode and the overall rectenna improvement for both the TWD and the lumped-element rectenna. Using a TWD instead of a lumped-element improves the coupling efficiency ~1700 times but only results in a overall performance improvement of ~14 times. The difference is due to plasmonic loss. In other words, the plasmonic loss can be calculated as 100%-(overall improvement)/(coupling improvement), specifically: (100%-14/1700).

Detailed Germanium Shadow Mask Fabrication

Figure S1: Step 1: Spin on DUV photoresist (PR) and print germanium shadow mask pattern in PR with DUV stepper

Figure S2: Step 2: Etch rectenna pattern into Ge layer with a CF_4 etch

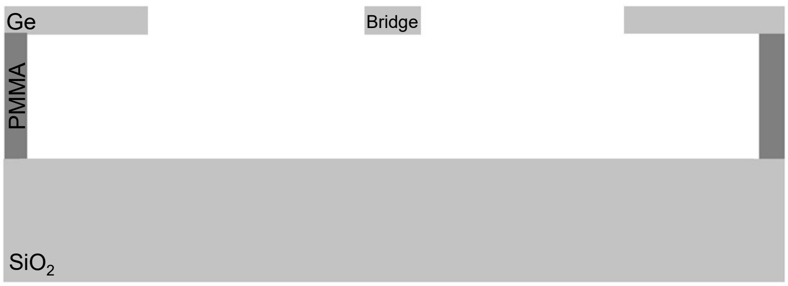

Figure S3: Step 3: Remove PMMA support layer with O_2 etch

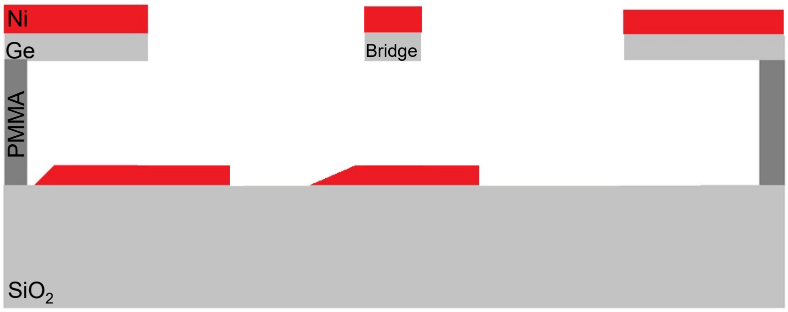

Figure S4: Step 4: Evaporate Ni at an angle from the right

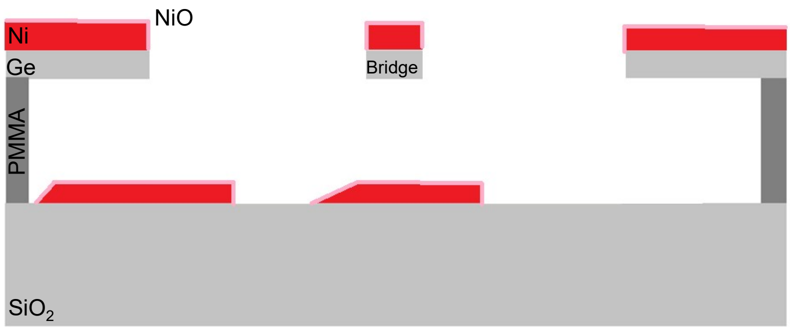

Figure S5: Step 5: Grow NiO in an O_2 plasma

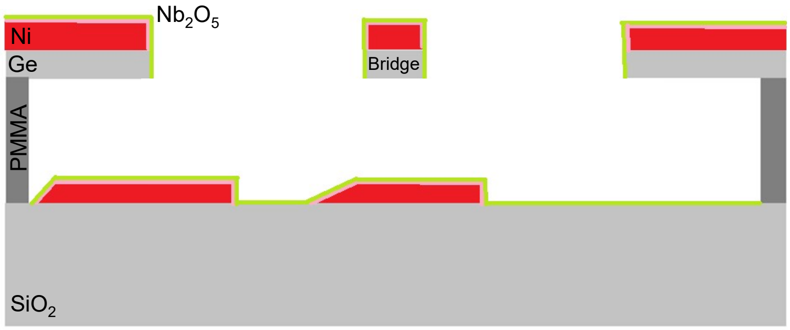

Figure S6: Step 6: Deposit Nb_2O_5 by DC reactive sputtering

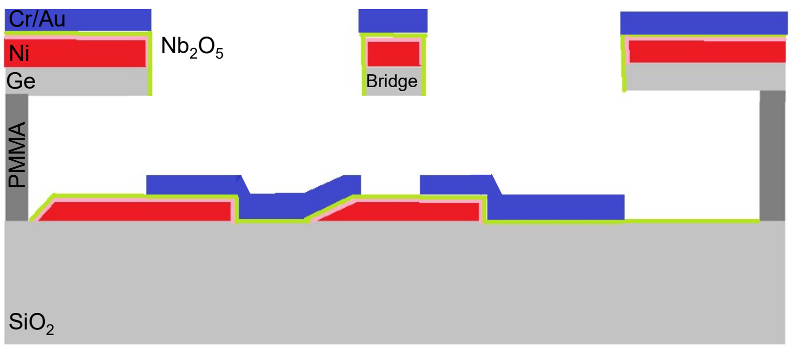

Figure S7: Step 7: Evaporate Cr/Au at normal incidence

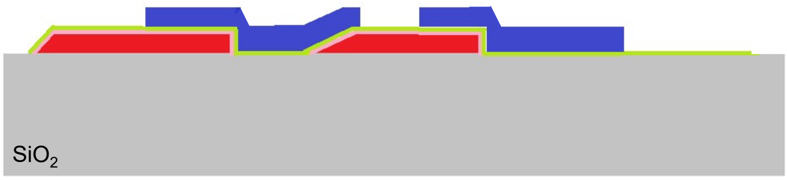

Figure S8: Step 8: Place sample in acetone bath to disolve PMMA and liftoff excess metals and oxides

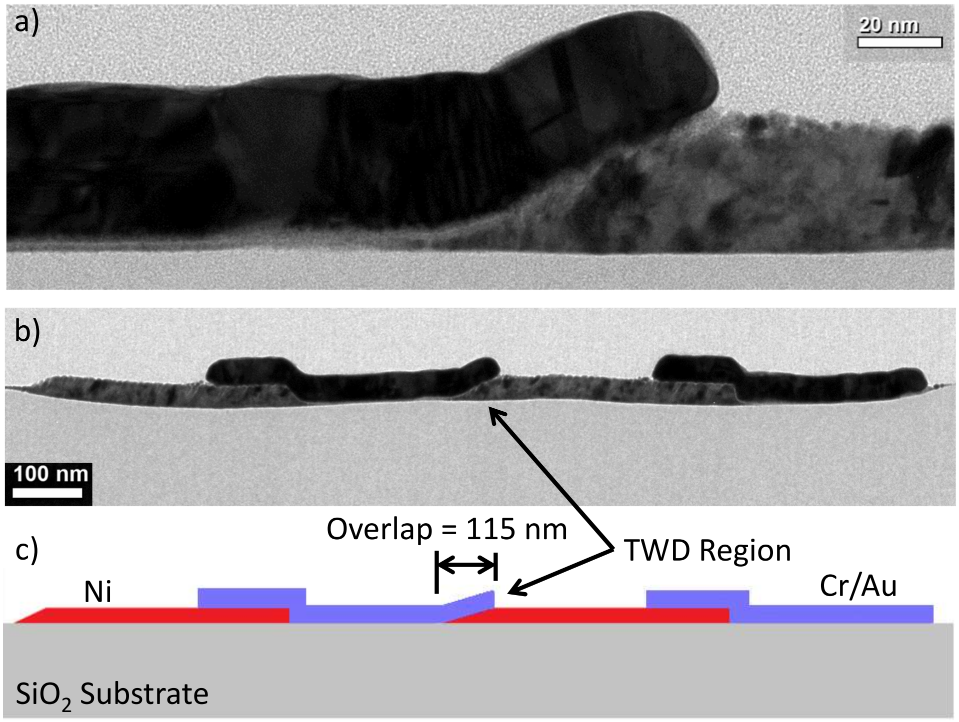

Figure S9: Enlarged TEM (Figure 4 in manuscript) (a) Shows a magnified cross-section of the MIM tunnel junction (b) expanded view of entire TWD structure (c) illustrated expanded TWD cross-section for comparison.