Complex conductivity of strongly disordered thin MoC superconducting films

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Abstract

The non-contact broadband transmission line flip-chip spectroscopy technique is utilized to analyze the complex conductivity of strongly disordered 5 nm thin molybdenum carbide films. This is achieved by probing resonances of the mm-sized, 2D kinetic planar MoC resonators in the GHz frequency range. The temperature dependence of the resonances was analyzed by the complex conductivity of disordered superconductor, which relates the Dynes superconducting density of states of highly disordered superconductors to their complex conductivity. The obtained Dynes broadening parameters relate reasonably to the ones estimated from scanning tunneling spectroscopy measurements. The resonances of the kinetic planar 2D resonator were simulated in Sonnet software, an Electromagnetic Field Solver Software. The 2D resonances of superconducting planar resonators could be further utilized, for example, as filters in sensitive superconductive electronics, such as circuit QED. The proper understanding of the nature of these resonances in 2D films can help to eliminate them in spectroscopic experiments and thus increase the precision of spectroscopic methods.

Experiment

Samples were prepared by magnetron sputtering, with different stoichiometric ratio and thickness. They were characterized by sheet resistance $R_s = \rho/t$, where t is sample thickness. The temperature dependence of the samples R_s was measured in parallel with broadband flip-chip transmission line spectroscopy, at temperatures down to 350 mK in He^3 sorption refrigerator. The spectra were measured by a vector network analyzer in GHz frequency range.

Complex conductivity

Complex conductivity of thin superconducting films was numerically calculated by the model of the complex conductivity of Dynes superconductors [2], with broadened density of states (DOS) with scattering parameter Γ. The temperature dependence of complex conductivity of disordered superconductors, which deviates from Mattis-Bardeen conductivity and the Dynes DOS are shown in fig. 1.

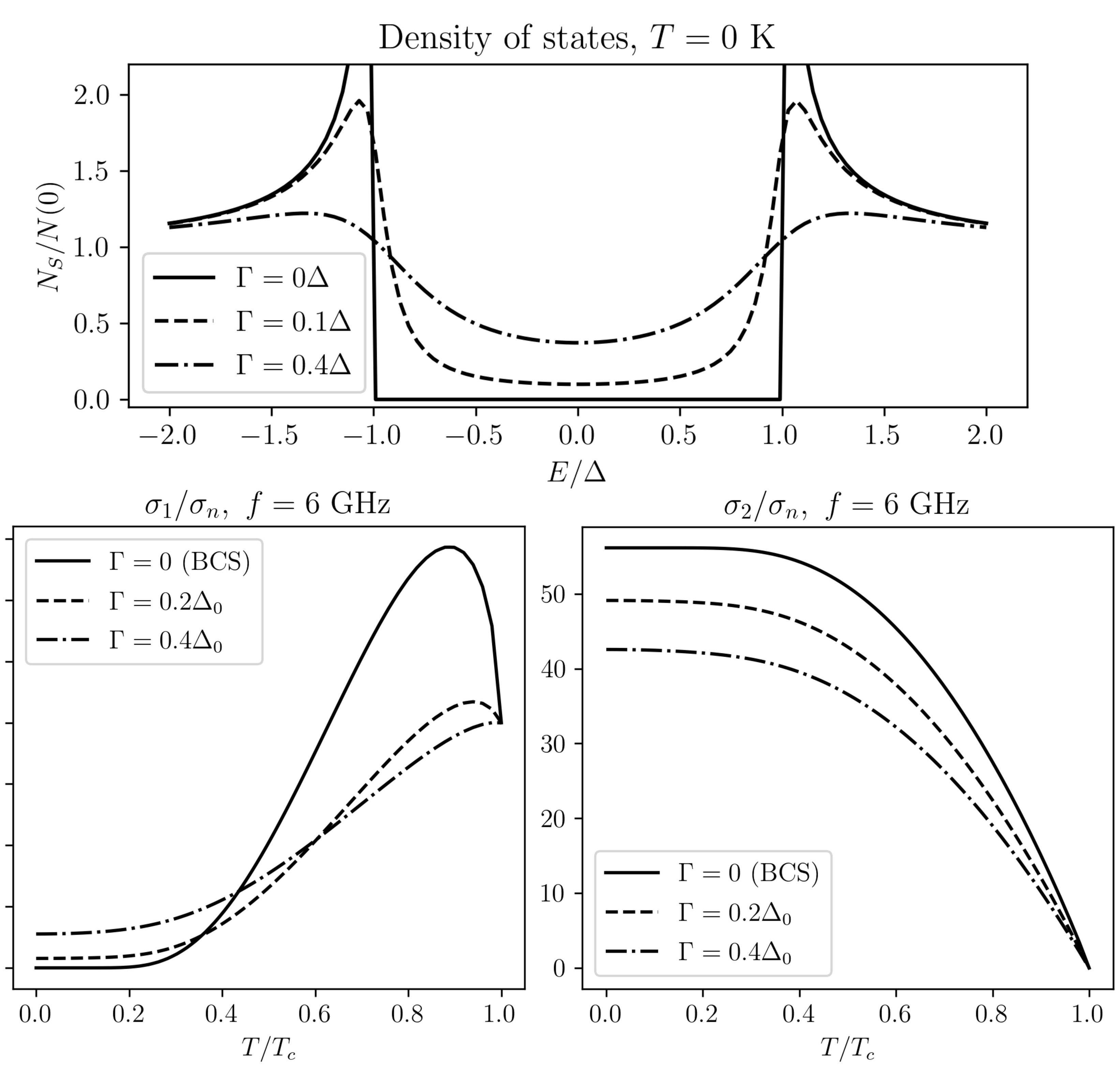

Figure 1: Top: Broadened DOS of Dynes model with Γ. Bottom: Temperature dependence of conductivity of Dynes model.

Measurements and numerical model

The measured resonances in transmission spectra, shown in fig. 2, were modeled as a lumped-element LC resonance circuit [1]:

$$\omega_n^r(T) = \frac{1}{\sqrt{(L_k + L_n)C_n}} = \frac{\omega_n^{(0)}}{\sqrt{1 + g_n L_k(\omega, T, \Delta, \Gamma)}}, \qquad (1)$$

where $\omega_n^{(0)}$ is n-th geometry-governed resonance frequency, g_n is coupling parameter of the n-th mode, $L_k = \sigma_2/(\omega\sigma^2)$ is the kinetic inductance of the superconductor. $\Delta_0 = 1.84\ k_B T_c$ and Γ were obtained from the fit. g_n and $\omega_n^{(0)}$ are fit parameters for each resonance mode. The fit of the resonances is shown on fig. 2.

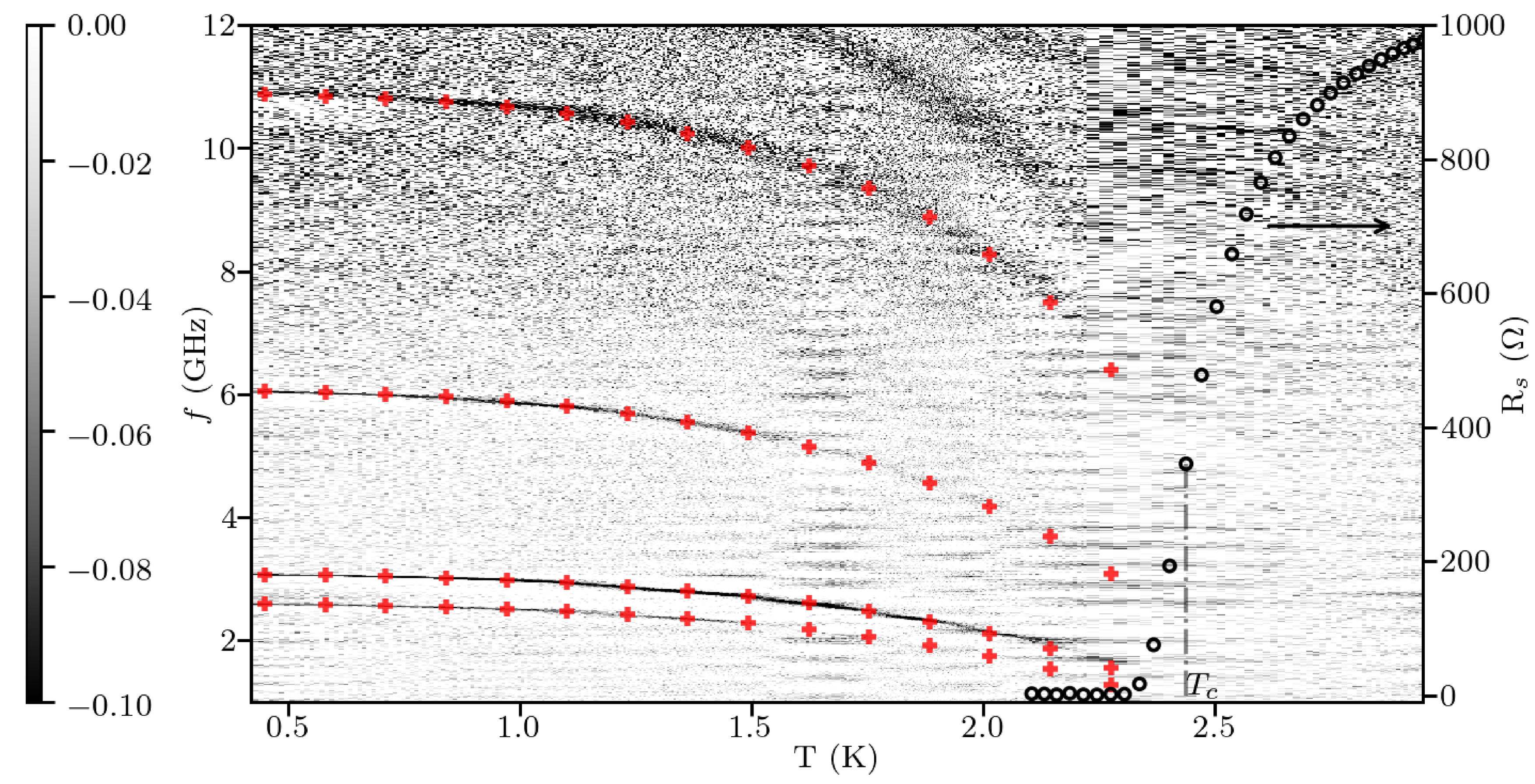

Figure 2: Transmission spectra (color coded) of a sample with $R_s = 970\Omega$. For presentation purposes, Savitzky–Golay filter was used to suppress the background. Red crosses and black circles represent fit of the resonances and DC resistance temperature dependence, respectively.

Results

Sample	R_s (Ω)	T_c^{DC} (K)	T_c^{spec} (K)	Γ^{spec}/Δ_0	Γ^{STS}/Δ_0
A	120	7.89	-	-	0
B	212	7.04	7.02	0	0.03
C	565	4.85	5.11	0.2	0.20
D	974	2.44	2.52	0.5	0.44

Table 1: Sample parameters: R_s is sheet resistance at room temperature, T_c^{DC} is superconducting critical temperature from transport measurement, T_c^{spec}, Γ^{spec}, and Γ^{STS} are values estimated from spectroscopic measurement in the GHz frequency range and from STS measurements, respectively.

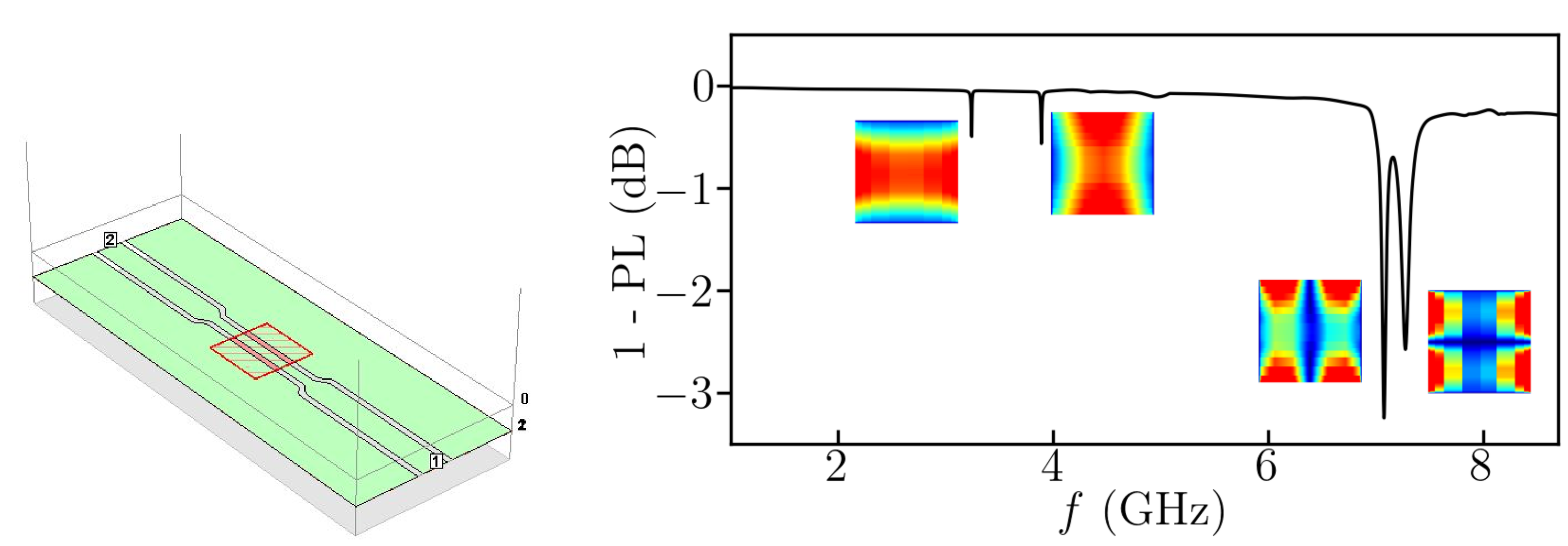

Figure 3: Left: Experiment model in Sonnet software. Right: Power loss simulated in Sonnet experiment, with color-coded current density j_y,j_x,j_x and j_y.

Conclusion

We utilized a broadband transmission line flip-chip spectroscopy technique to study the superconducting transition of thin, strongly disordered MoC films sputtered on sapphire substrates. The dynamics of observed resonances in transmission spectra is dominantly governed by the complex conductivity of the disordered films and dimensions of the films, as simulated in Sonnet software, shown in fig. 3. This non-contact method could be used to estimate the Γ and T_c of highly disordered films, avoiding the non-trivial calibration procedure required in similar spectroscopic techniques.

References

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