Subharmonic energy gap structure in the Josephson radiation at 35 GHz from a superconducting thin-film microbridge

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Published in:
Applied Physics Letters

Link to article, DOI:
10.1063/1.90910

Publication date:
1979

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Hansen, J. B., Levinsen, M. T., Lindelof, P. E., Dueholm, B., Mygind, J., Pedersen, N. F., & Sørensen, O. H. (1979). Subharmonic energy gap structure in the Josephson radiation at 35 GHz from a superconducting thin-film microbridge. Applied Physics Letters, 35(1), 28-30. DOI: 10.1063/1.90910

and Xe_2^* molecules and Xe^+. This broadband spectrum indicates that the laser should be tunable over a wavlength range of several tens of nanometers. Plates taken of the fluorescence emission with the mirrors removed show a broad continuum emission extending over approximately 100 nm and exhibiting a few discrete absorption and emission lines. Surprisingly, this spectrum does not show the broad peak at approximately 460 nm reported by Brashears and Setser but more closely resembles their low-pressure spectrum.[4] This could imply that the *C* state is formed in high vibrational levels which are not fully relaxed under our conditions (3 atm He). An alternate explanation is that the 460-nm XeF spectrum obtained by Brashears and Setser with 200 Torr of Kr buffer actually contains contributions from excited triatomic XeKrF* molecules, which are expected to emit in this spectral region.[8]

It is evident from the results of this work that the performance of the present device is limited by the low value of the small signal gain combined with the short time available for the buildup of stimulated emission. This is illustrated by the photodiode trace in Fig. 2, which shows that the 480-nm lasing reaches its peak when the excitation pulse is essentially over. The performance of the $C \rightarrow A$ laser could be enhanced by extending the duration of the pumping pulse to allow the cavity intensity to build up to saturation. Alternatively, more efficient extraction of energy might be achieved from the present device by injecting a signal into a regenerative amplifier in order to saturate the medium before the gain terminates. Efforts to improve the laser performance using these techniques are presently underway.

Since the XeF excited states are efficiently produced by discharge excitation, the $C \rightarrow A$ transition has the potential for an efficient high-power gas laser tunable over a bandwidth of approximately 40 nm in the visible. In order to realize this potential, a method will have to be found to saturate the $C \rightarrow A$ transition in order to compete effectively against excited-state losses through the higher-gain $B \rightarrow X$ transition.

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(Received 21 March 1979; accepted for publication 3 April 1979)

Nonresonant detection of the Josephson radiation 35 GHz from a superconducting thin-film microbridge is reported. The high frequency and the accuracy of these measurements lead to a new important observation: subharmonic energy gap structure in the detected integral power. The maximum integral power measured was as large as 8×10^{-11} W.

PACS numbers: 74.50. + r, 85.25. + k, 73.40.Jn, 73.60.Ka

In recent years there has been a considerable interest in superconducting thin-film microbridges. The very small capacitance of these bridges makes them suitable for high-frequency applications. Furthermore, their properties can be approximately characterized by the resistively shunted Josephson-junction model (RSJ model).[1] The bottleneck for high-frequency applications of microbridges is the Joule heating produced in the bridges. The heating problem is minimized when the microbridge is three dimensional with a high normal-state resistance.[2]

Previously, the high-frequency behavior has been probed indirectly by looking for microwave-induced steps in the *I-V* characteristics.[3] It is evidently of importance to probe the autonomous Josephson oscillation at high frequencies. The Josephson radiation has already been observed up to *X*-band frequencies (12 GHz).[4] In this letter we report the first direct detection of Josephson radiation from a thin-film microbridge at 35 GHz. Measuring at higher frequencies has important diagnostic advantages. It may be shown that the condition for coincidence between the gap frequency and the detector frequency ν_D is governed by $T_C - T \propto \nu_D^2$. The corresponding integral power scales as ν_D^4.

The high frequency used in this experiment enables us to investigate directly the subharmonic energy gap structure (SGS) in the Josephson radiation. Previously, the SGS has only been observed in the dc *I-V* characteristics of Josephson junctions.[5]

The details of the experiment were similar to those reported at *X* band in Ref. 6. The microbridges were cross-scratched[1] in an indium film and mounted directly across the

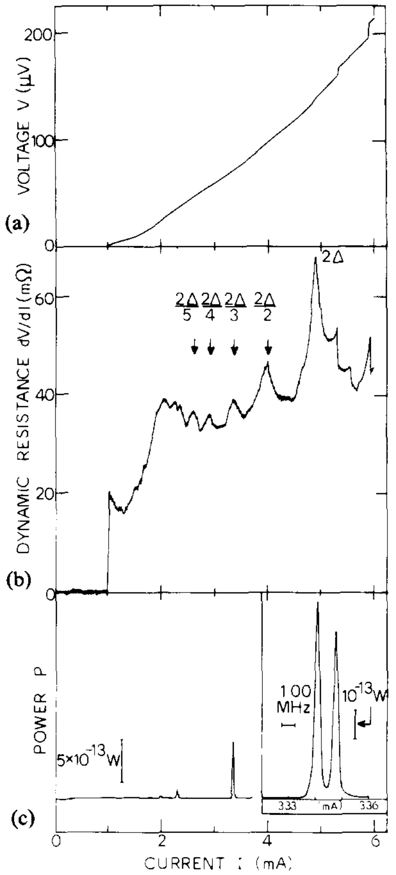

FIG. 1. Results for a cross-scratched thin-film indium microbridge on a glass substrate. Film thickness, 0.42 μm. Bridge parameters: length ~ 0.3 μm, width $\sim 0.5\,\mu$m, height $\sim 0.2\,\mu$m, RRR = 33, $T_c = 3.40$ K, $dI_c/dT = 15.4$ mA/K, $R_N = 41$ mΩ. (a) Typical I-V characteristic ($T = 3.33$K); (b) The corresponding derivative characteristic; and (c) The power detected at 35 GHz in a 10-MHz 3-dB bandwidth as a function of current. The inset shows the fundamental peak on an expanded scale; the frequency axis was calculated from the dynamic resistance at the particular current.

low-impedance end of a two-step binomial microwave transformer with an impedance ratio of 60 and a matched calculated bandwidth of 3 GHz. The 35-GHz receiver was a conventional superheterodyne detector with a noise figure of 7 dB (double sideband). Two different intermediate frequency (i.f.) amplifiers were used in the experiment. One at 70 MHz with a 3-dB bandwidth of 10 MHz, and the other at 160 MHz with a 3-dB bandwidth of 145 MHz. In the temperature range investigated in detail, $0.9 < T/T_c < 1$, the linewidth of the Josephson radiation was as small as 80–40 MHz. Hence, the first i.f. amplifier was used to investigate the linewidth of the radiation whereas the second was used to measure the integral power.[8] The microwave transformer and the microbridge were enclosed in a vacuum can immersed in liquid helium. The temperature was stabilized to within 10^{-5} K using an electronic feedback system.

Figure 1(a) shows a typical I-V characteristic for a superconducting microbridge of indium. The dominant structure in the derivative of the I-V characteristic is the SGS, as shown in Fig. 1(b). The maxima in the dynamical resistance are usually interpreted as the voltages corresponding to submultiples of the energy gap. Using this identification the energy gap decreases with increasing voltage across the bridge as seen from Fig. 1(b). This behavior is caused by the temperature rise in the bridge as the Joule heating increases with increasing voltage.[2] In a nearly two-dimensional bridge with a small normal-state resistance, as is the case with the bridges considered here, heating is particularly destructive to the ac Josephson effect. The ac Josephson effect is, in fact, extinguished at a voltage just above the $2\Delta/e$ peak in the SGS. It should be emphasized that while measuring the derivative of the I-V characteristics no feedback structures (self-resonances) caused by the microwave transformer could be observed.

Figure 1(c) shows the video output from the detector as a function of current. The first three harmonics of the fundamental Josephson frequency are observed. At lower temperatures up to 13 harmonics could be resolved. The inset in Fig. 1(c) shows the detected power of the fundamental Josephson frequency at 35 GHz on a 50-times expanded current scale. This trace was recorded using the 70/10 MHz i.f. amplifier, and the two sidebands 140 MHz apart are clearly distinguished. The linewidth of the Josephson radiation is 41 MHz in this case. The difference in magnitude between the two sidebands reflects the slight frequency dependence of the microwave coupling to the microbridge. When measuring the integral emitted power using the 160/145 MHz i.f. amplifier, the local oscillator frequency was chosen such

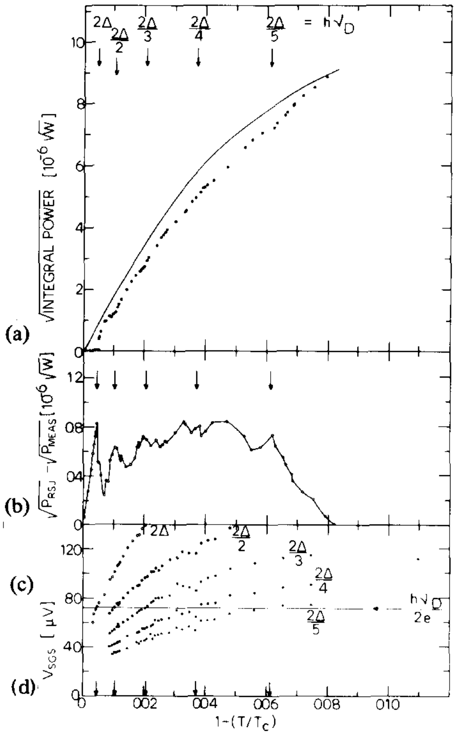

FIG. 2. Same bridge as in Fig. 1. (a) The square root of the integral power at 35 GHz versus temperature. The full curve is the prediction of the RSJ model with a load resistance of 58 Ω. (b) The difference between the experimental points and the theoretical curve in (a). (c) The voltage positions, V_{SGS}, of the maxima in the dynamic resistance of the I-V characteristic [see Fig. 1(b)], alias the subharmonic energy gap structure. The horizontal line indicates the voltage (72.4 μV) where the fundamental frequency in the Josephson radiation corresponds to the detector frequency ν_D, and the crossings indicated by the arrows give the temperatures where this voltage coincides with the subharmonic energy gap voltages.

that the change in microwave coupling over the 145 MHz of the lower sideband was negligible. The Josephson radiation linewidth is found to be proportional to the square of the dynamic resistance; the corresponding effective noise temperature is 30 K (as defined in Ref. 7). For fixed temperature in the range investigated, the change in the dynamic resistance over the linewidth of the radiation could be neglected.

The integral power was measured by means of the broadband (145 MHz) i.f. amplifier. Since the linewidth is much narrower than the bandwidth, the maximum detected signal is a measure of the integral power.[8] Figure 2(a) shows the square root of the integral power in the fundamental Josephson oscillation at 35 GHz plotted versus temperature close to T_c. The RSJ model predicts the following expression for the square root of the power dissipated in a load resistance R_L at the detector frequency ν_D:

$$\sqrt{P} = (h\nu_D/2e)(2/R_L)^{1/2}[(1+\Omega^2)^{1/2}-\Omega], \qquad (1)$$

where $\Omega = h\nu_D/2eR_N I_c$. The product of the normal-state resistance R_N and the critical current I_c has a universal value for these small bridges, $R_N I_c = 635(1 - T/T_c)\,(\mu V)$. Hence, Eq. (1) has only one adjustable parameter, R_L. The full curve in Fig. 2(a) is calculated using $R_L = 58\Omega$. The fitting factor, R_L, includes impedance mismatch, attenuation in the waveguide, dissipation in the substrate, etc. A rough estimate which includes the self-inductance of the thin film in series with the bridge shows that the detected power is of the same order of magnitude as the value expected with the present setup. Figure 2(b) shows the difference between the RSJ model and the experiment. At certain temperatures the difference exhibits peaks which can be correlated with the SGS in the *I-V* characteristic. In Fig. 2(c) the voltage positions of the maxima in the dynamic resistance [see Fig. 1(b)] are plotted versus temperature. The arrows in Fig. 2(c) identify the temperatures at which submultiples of the energy gap in the bridge cross the votlage over the bridge that corresponds to the detector frequency through the Josephson *V-ν* relationship. These temperatures are seen to coincide with the temperatures at which relative depressions in the emitted power occur [the peaks in Fig. 2(b)]. Note also from Fig. 2(a) that power can only be observed at temperatures where $2\Delta\,(T) > h\nu_D$ (2Δ from the SGS).

It has sometimes been argued that the theory for Josephson tunnel junctions is valid also for microbridges. Although this has no theoretical justification so far, it is certainly of interest to investigate the ac Josephson effect at frequencies around the gap frequency (where Josephson tunnel junctions exhibit the Riedel singularity) since it is already known that microbridges show subharmonic energy gap structure. The present investigation indicates that the Josephson amplitude is suppressed at frequencies given by $h\nu = 2\Delta/Ne$ (where N is an integer) corresponding to submultiples of the energy gap in the bridge. It is thus natural to expect that the same mechanism is responsible for this phenomenon as well as for the subharmonic energy gap structure found in the dc *I-V* characteristic of microbridges. We want to point out that we have detected so far the largest amount of microwave power (8×10^{-11} W) from a single thin-film microbridge at the highest frequency (35 GHz) where Josephson radiation has been detected. This power exceeds by an order of magnitude the detected power at 9 GHz.[6] This is qualitatively in agreement with the RSJ model which predicts an integral power that increases as ν^2 (assuming similar matching conditions at the two frequencies). Our result gives promise for high-frequency applications of thin-film microbridges.

B. Krogh and L. Olsen are acknowledged for their assistance with the electronic system and Ole Eg for the sample preparation. This research was supported by the Danish Natural Science Research Council projects Nos. 511-7048, 511-10160, 511-5616, 511-8527, 511-8048, 511-10098, and 511-10279.

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