Tunable anisotropic nonlinearity in superconductors with asymmetric antidot array

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The influence of the spatial asymmetry of the pinning potential on the spectral composition of the voltage, induced in perforated superconducting Al bridges by the injection of a sinusoidal bias current, was investigated. The loss of the mirror symmetry of the pinning potential leads to the appearance of even Fourier components in the induced voltage in the vicinity of the superconducting phase transition line on the H - T diagram (H is the external magnetic field, and T is the temperature). Artificially-introduced asymmetry for vortex motion makes it possible to create low-resistive materials, in which nonlinearity depends on the direction of injected electrical currents.

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The controlled manipulation of magnetic flux quanta (or vortices) in superconducting films under the action of non-equilibrium fluctuations or external excitations with zero average (vortex ratchet) has recently attracted a lot of interests (see, e.g., Refs. 1–15 and references therein). A preferable vortex motion in a certain (“easy”) direction can be experimentally realized in various one-dimensional (1D) and two-dimensional (2D) systems of reduced symmetry: in films modulated by triangular dots,⁷ in perforated films with regular arrays of asymmetric antidots,^{8–11} in mesoscopic singly connected superconductors,¹² and in superconductors placed in a spatially modulated magnetic field.^{13–15} All these systems can be potentially used for designing flux pumps for removal of unwanted trapped flux in superconducting devices,¹ and dc rectifiers (diodes).

In this letter, we are aiming at the generalization of the concept of unidirectional vortex dynamics in a ratchet potential for the case of *higher harmonics generation*. Indeed, passing an alternating current of certain frequency f through any medium should generally induce voltage oscillations at multiple frequencies nf (n is integer). However, the appearance of even harmonics (regardless on the frequency range) is known to be forbidden for a material with spatial inversion or mirror plane symmetry.¹⁶ One can expect that an artificially introduced asymmetry for vortex motion, occurring in all ratchet systems, will lead to a nontrivial nonlinear response. In the presence of a ratchet potential the static I - V dependence of the perforated superconducting bridge will lose symmetry,¹⁷ $V(I) \neq -V(-I)$. Since the voltage drop in a sample should be zero at $I=0$, the expansion of V versus I in power series has the following form: $V = \alpha_1 I + \alpha_2 I^2 + \alpha_3 I^3 + \dots$, where α_i are the constants depending on the external magnetic field H and temperature T . Substituting $I(t) \sim \sin(2\pi ft)$, one can see that the time-dependent voltage $V(t)$ oscillates at multiple frequencies, including zero frequency. Provided $V(I) = -V(-I)$, both the diode effect and the even Fourier components should disappear. It is worth noting

that breaking the sample symmetry in 2D superconducting films can affect only a certain direction, while keeping the symmetry in the perpendicular direction unaltered. It gives us a possibility to fabricate an artificial material with anisotropic nonlinearity, depending on the orientation of the injected electrical currents.

Two perforated Al microbridges of the width $600 \mu\text{m}$ and thickness $d=50 \text{ nm}$, which have the critical temperatures T_c close to 1.3 K, were prepared by dc sputtering on a Si/SiO₂ substrate. The pinning landscape, prepared with electron beam lithography, has the period $a=3000 \text{ nm}$ and it can be represented as a superposition of two interpenetrated square sublattices of big and small microholes (“antidots”) of $1200 \times 1200 \text{ nm}^2$ and $600 \times 600 \text{ nm}^2$ in size (Fig. 1). Depending on the separation s between centers of these antidots, the resulting complex array can be symmetrical ($s=1500 \text{ nm}$) or asymmetrical ($s=1100 \text{ nm}$) with respect to the y -axis. For brevity, we introduced notations “sample S” and “sample A” (either symmetrical or asymmetrical pinning potential).

Our ac four-probe measurements were carried out as follows: a sinusoidal driving current $I = I_{ac} \sin(2\pi ft)$, applied to such a bridge (the amplitude $I_{ac}=141 \mu\text{A}$ and the frequency $f=1.11 \text{ KHz}$), generates a voltage drop $V(t)$. This time-dependent voltage can be represented as $V(t) = \sum_{n=0}^{\infty} V_{nf} \sin(2\pi nft + \varphi_n)$, where V_{nf} and φ_n are the amplitude and the phase of the n th Fourier component. The am-

FIG. 1. (Color online) (a) A schematic view of the perforated superconducting Al bridge, [(b) and (c)] Atomic force microscopy images of samples A and S. The white dashed lines depict the unit cells ($3 \times 3 \mu\text{m}^2$).

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FIG. 2. (Color online) The dependencies of the voltage V_{nf} , measured at zero, fundamental, double, and triple frequencies, on the external magnetic field H and temperature T : (a) V_0^S , (b) V_0^A , (c) V_f^S , (d) V_f^A , (e) V_{2f}^S , (f) V_{2f}^A , (g) V_{3f}^S , and (h) V_{3f}^A . Only one-half of the H - T diagrams were shown since $|V_{nf}(H, T)| = |V_{nf}(-H, T)|$. The solid black lines correspond to the conditions $V_{nf}(H, T) = \alpha \max V_{nf}$, $\alpha = 0.1, 0.5, 0.95$. All insets show the dependencies of the Fourier components of the mean instant velocity $\langle u_{y,nf}^S \rangle$ and $\langle u_{y,nf}^A \rangle$ on H and the effective inverse temperature U_p/E_0 , calculated with the assumption of the logarithmic intervortex interaction $V(r) = -E_0 \ln(r/\lambda)$, where U_p is the pinning energy. Note that the periodic changes in $\langle u_{y,nf}^S \rangle$ as well as $\langle u_{y,nf}^A \rangle$ and $\langle u_{y,3f}^S \rangle$ at sweeping H resemble the variations of the Fourier components of the voltage. Color scales for all plots and insets are chosen in the same way.

plitudes of the first, second, and third Fourier harmonics V_f , V_{2f} , and V_{3f} as well as the dc voltage V_0 as functions of the transverse magnetic field H and temperature T were measured by the lock-in amplifier Signal Recovery 7225 and the nanovoltmeter Hewlett Packard 34420A. All experimental results are summarized in Fig. 2.

We begin with the discussion of the H - T diagrams of the linear response V_f^S and V_f^A , measured for samples S and A at the fundamental frequency [panels (c) and (d) in Fig. 2]. The occurrence of resistivity minima at integer occupation numbers $m = H/H_1$ in both samples indicates the formation of very stable vortex configurations. Here $H_1 = \Phi_0/a^2 \approx 0.22$ mT is the first matching field, at which the sample is threaded by one magnetic flux quantum, $\Phi_0 = 2.07 \times 10^{-15}$ Wb, per unit cell. The broader resistive transition of the sample S in comparison with the sample A (at the same T/T_c ratio) can be attributed to the enhanced surface superconductivity, since the antidots in sample S are distributed more uniformly across the sample area.

As expected, the loss of mirror symmetry of the pinning landscape along the y -axis significantly increases the dc rectification for sample A [compare panels (a) and (b) in Fig. 2]. The voltage pattern in the H - T diagram demonstrates the series of sign inversions which were recently explained in Ref. 10 by taking into account the intervortex interaction for a dense vortex lattice in the presence of a ratchet potential. Under the same conditions, the diode effect for sample S is practically absent, except in the vicinity of the third matching field ($H/H_1 \approx 3$). The origin of such ‘resonant’ rectification for the nominally symmetrical sample is currently unclear.

The H - T diagrams of the response at the second Fourier harmonic, V_{2f}^S and V_{2f}^A , seem to be similar to that for the dc

response in many respects [compare panels (a), (b), (e), (f) in Fig. 2]. Due to a larger ‘signal-to-noise’ ratio for measurement of the second Fourier harmonic in comparison to dc measurements, this modulation measurements appear to be more effective for probing the symmetry properties of samples. Finally, we showed the results of the measurements at the triple frequency, $V_{3f}^S(H, T)$ and $V_{3f}^A(H, T)$ [panels (g) and (h)]. We emphasize that the field-induced oscillations of the critical temperature, related to the formation of stable vortex structures, become more pronounced as compared with the T_c oscillations observed in the linear response. Thus, the experimental treatment of the nonlinear response is a rather sensitive and powerful technique for studying the commensurability effects in nanostructured superconductors.

In order to illustrate correlations between the symmetry of the pinning potential and the spectral composition of the induced voltage, we simulated the low-frequency dynamics of a vortex chain in an asymmetrical 1D periodic potential¹⁰ under the sinusoidal current excitation and estimated the instant mean vortex velocity $\langle u_y(t) \rangle = \sum_{i=1}^N \dot{y}_i / N$ (N is the number of vortices). We considered both long-range vortex-vortex interaction, $V(r) = -E_0 \ln(r/\lambda)$, and short-range one, $V(r) = E_0 K_0(r/\lambda)$ (K_0 is the modified Bessel function), used recently for describing ratchet phenomena in superconducting systems with the period comparable with the penetration length λ .¹⁵ The Fourier components of the instant mean vortex velocity, $\langle u_y \rangle_{nf} = |\int_0^{1/f} \langle u_y(t) \rangle e^{-2\pi i n f t} dt|$, as well as its dc value, $\langle u_y \rangle_0 = \int_0^{1/f} \langle u_y(t) \rangle dt$, are expected to determine the main contribution to the spectrum of the voltage: $V_0 \propto H \langle u_y \rangle_0$ and $V_{nf} \propto H \langle u_y \rangle_{nf}$. It was found that independently on the type of the intervortex interaction, this simple model does explain how an ac excitation of interacting vortices in the ratchet potential leads to a generation of even Fourier harmonics observed experimentally. The results of our simulation are plotted in the $H/H_1 - U_p/E_0$ plane (see the insets of Fig. 2), where U_p is the characteristic pinning strength. Since U_p is known to decrease at increasing temperature and vanish at $T = T_c$,¹⁸ we can consider a wide range of the pinning strengths (and temperatures), starting from $U_p = 0$. It should be noted that our 1D model cannot describe the rectification at $|H| \approx 3H_1$ for sample S. This indicates out that the dynamics of 2D vortex lattice in the 2D pinning potential is crucial for the explanation of all observed peculiarities in nonlinear response. However, this issue goes beyond the subject of this letter, and the detailed treatment in the framework of a full 2D model similar to that used in Refs. 6 and 15 will be considered separately.

In summary, we presented a comparative study of the linear and nonlinear properties of the perforated superconducting films. We demonstrated that the nonlinear properties of the nanostructured superconductors can be tuned by making the pinning landscape of a required symmetry, and thus we proposed a tunable vortex frequency converter. Interestingly, such a symmetry-breaking induced harmonics generation could be a basis for a designing the materials with an anisotropic nonlinearity.

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