Flux-periodic resistance oscillations in arrays of superconducting weak links based on InAs-AlSb quantum wells with Nb electrodes

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InAs-AlSb quantum wells contacted with periodic gratings of superconducting Nb electrodes show Josephson-junction characteristics at low temperatures. When a nonzero resistance is reestablished by a weak magnetic field, the resistance shows a strong component periodic in the magnetic field. At fields above $\sim 300\ \mu$T, the oscillation period corresponds to one flux quantum per grating cell; but in wide arrays ($\geqslant 40\ \mu$m), a frequency doubling takes place at low fields, indicating the formation of a staggered vortex superlattice at twice the lithographic period. [S0163-1829(96)50628-4]

There has recently been a growing interest in superconducting weak links in which the conducting medium coupling the superconducting banks is the quasi-two-dimensional electron gas (2DEG) in a semiconductor heterostructure, especially a structure employing a conducting channel of InAs,[1–3] a material that has the advantage that clean metal-InAs interfaces do not exhibit Schottky barriers.[4] Due to the very high electron mobilities and long mean free paths in such structures, the weak links have properties significantly different from those of more conventional weak links.

In the present paper we report on flux quantization effects in *arrays* of 2DEG-coupled weak links, as they manifest themselves in the magnetic-field dependence of the zero-bias resistance of the arrays. Flux quantization effects are a fundamental feature of arrays of Josephson junctions (JJ's), and there is a rich literature on this topic, both in general monographs[5,6] and in conference proceedings specifically dedicated to this topic.[7] To the best of our knowledge, ours is the first study of such effects for arrays of 2DEG-coupled weak links.

In contrast to the majority of the arrays discussed in the literature, our arrays, first described in a 1994 paper,[2] are one dimensional, as shown schematically in Fig. 1: A modulation-doped InAs quantum well with AlSb barriers, grown by molecular beam epitaxy (MBE), is contacted periodically with a grating array of superconducting Nb electrodes. Except for a current bypass path underneath each individual Nb line, the structures resemble series connections of large numbers (typically ≈ 300) of individual weak links. At sufficiently low temperatures (in some samples as high as ≈ 6 K), such arrays exhibit current-voltage characteristics very similar to ordinary JJ's, except for the greatly expanded voltage scale due to the multiple series connection (Fig. 2). The sample shown was prepared from an MBE-grown InAs quantum well with a thickness $w = 15$ nm, an electron sheet concentration of $5.5\times 10^{12}\ \mathrm{cm}^{-2}$, and a low-temperature (12 K) electron mobility of $210\,000\ \mathrm{cm}^2/\mathrm{V\,s}$, corresponding to an (elastic) mean free path of about 6 μm (making allowance for nonparabolicity). The grating structure had a period $a = 0.96\ \mu$m and an array width $b = 95\ \mu$m; there were ~ 310 lines between the voltage electrodes, with a gap $L \approx 0.5\ \mu$m between the lines. More technological details have been given elsewhere.[2,8]

When a weak magnetic field B is applied perpendicular to the sample plane, a measurable zero-bias resistance gradually reappears, but—and this is the key point—containing an oscillatory component. Figure 3 shows the phenomenon as exhibited by the sample of Fig. 2. At fields above approximately 300 μT, the oscillations show a well-defined period

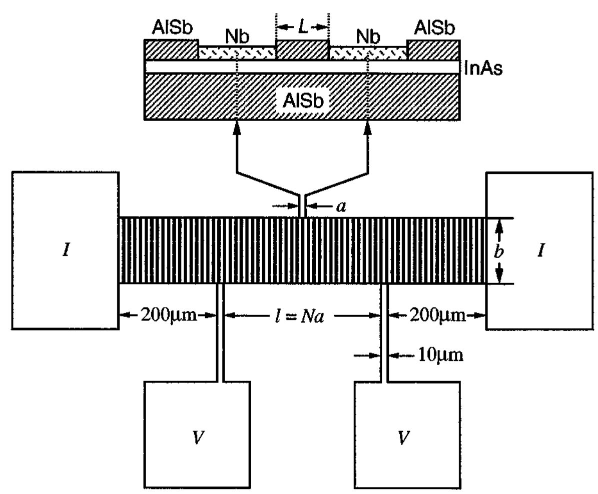

FIG. 1. Schematic overall layout (bottom) of the Nb grating structures studied in this work, along with (top) a cross section through a pair of Nb lines separated by a narrow stripe of InAs-AlSb quantum well. All I-V measurements are four-point measurements, made by imposing a current I via the outer contacts and measuring the voltage V between the inner contacts.

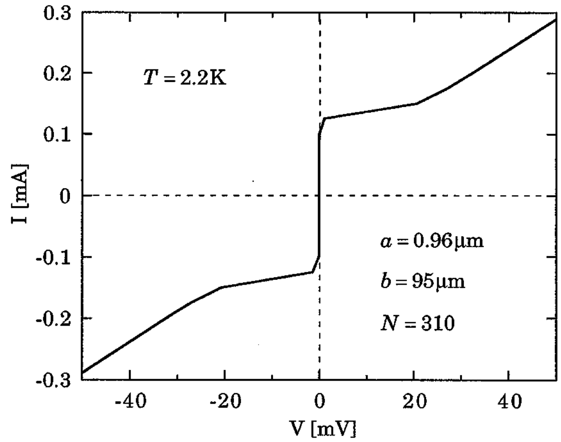

FIG. 2. Josephson *I-V* characteristic at 2.2 K for a typical sample with the geometry shown in Fig. 1. The rounding of the corners of the characteristic (not seen in all samples) is believed to reflect variations in the critical current of the individual weak links in the array. The corner current $I \approx 0.12$ mA corresponds to an (average) current density in the quantum well of $J_0 = I/bw \approx 8400$ A/cm^2.

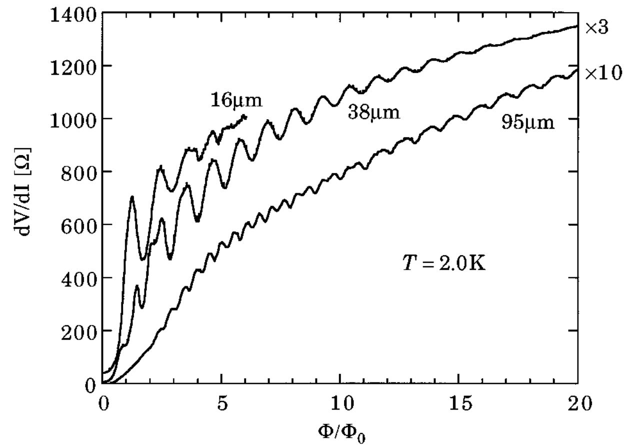

FIG. 4. Zero-bias differential resistance at 2 K as a function of nominal magnetic flux per cell, $\Phi = Bab$, for the sample of Figs. 2 and 3, both for the original line length of 95 μm, and after the line length was shortened by etching, first to 38 μm, and then to 16 μm. The nonzero resistance of the 16-μm sample for $B=0$ is believed to be the result of damage to some of the Nb lines during the reprocessing of the sample to reduce the array width, leading to the loss of superconductivity across one or more of the grating cells.

ΔB of about 24 μT. This clearly is a quantum interference effect similar to the oscillations observed in arrays of conventional JJ's.[7] If we express the period in terms of the *nominal* magnetic flux $\Phi = Bab$ "funneled" by the grating through each grating cell, we obtain a nominal flux period $\Delta\Phi = \Delta Bab = 2.2 \times 10^{-15}$ T m^2, a value close to the canonical superconducting flux quantum $\Phi_0 = \pi\hbar/e = 2.07 \times 10^{-15}$ T m^2. The qualifier "nominal" refers to the fact that the actual flux per cell should be slightly smaller, as a result of lateral flux expulsion from each cell at the end of the grating lines; the agreement would be perfect if we assume that the flux expulsion is equivalent to a line shortening by about 5.2 μm. With increasing field, the oscillations persist,

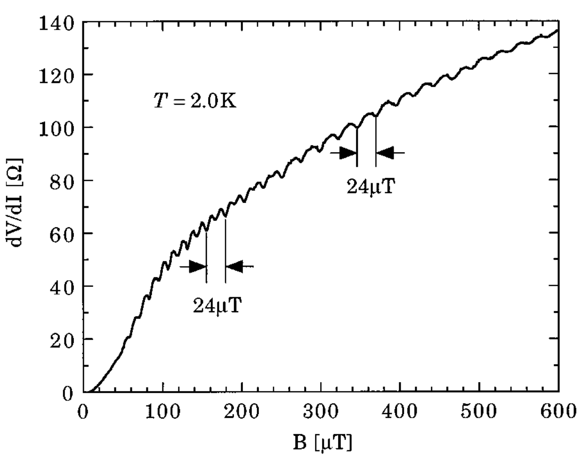

FIG. 3. Dependence of zero-bias resistance at 2.0 K on magnetic field, for the sample of Fig. 2. The field was applied via a small solenoid; the laboratory background field was excluded by a superconducting Pb shield, confirmed by checking for symmetry under reversal of the *applied* field. The resistance was measured by imposing a small ac current (typically 2 μA at 497 Hz) on the sample and measuring the synchronous ac voltage between the voltage terminals using a lock-in amplifier.

with the same period but a slowly decreasing amplitude, up to about 1 mT (not shown), that is, for more than 40 oscillation cycles, corresponding to over 40 vortices per cell.

At fields *below* ≈ 300 μT, additional resistance minima gradually evolve with decreasing field, exactly halfway between the "Φ_0 minima." At fields below ≈ 60 μT, corresponding to about three vortices per cell, the oscillations disappear altogether. Both the period and the phase of the oscillations are temperature independent; but their amplitude decreases with increasing temperature; they have essentially disappeared at 4.2 K. Although we observe significant *quantitative* sample-to-sample variations, the overall oscillation pattern was very robust, and shown by all recent samples[9] with similar array widths and grating periods, over the range of electron sheet concentrations investigated, from 5.5 to 9.5×10^{12} cm^{-2}, with corresponding mobilities ranging from 210 000 to 55 000 cm^2/V s, respectively.

Due to the large array width b, the individual junctions in the arrays are what is commonly referred to as *long* JJ's, in the sense that the line length b is large compared to the Josephson penetration depth λ_J. To estimate λ_J, we assume a critical Josephson current density J_c equal to the value $J_0 \approx 8400$ A/cm^2 quoted in Fig. 2, and an *effective* gap $L' = 0.6$ μm, slightly larger than the lithographic gap L, to allow for the penetration of the magnetic field into the Nb stripes ($L' \approx L + 2\lambda_L$, where λ_L is the London penetration depth, about 0.04 μm for Nb). This yields $\lambda_J \approx 2.3$ μm, a value much shorter than the array width $b = 95$ μm, but much larger than the thickness w of the current-carrying quantum well.

In order to study the effect of a change in array width, unencumbered by unrelated sample-to-sample variations that might obscure the width dependence, we decreased the width b of the existing grating of the sample of Fig. 3 by wet etching, first to about 38 μm, and then to 16 μm. The results, plotted in Fig. 4 in terms of Φ rather than B, show that the oscillation periods at high fields are again slightly larger than Φ_0, indicating the expected scaling with cell size, but again calling for some end corrections for flux expulsion. For the 38-μm sample, the end correction needed is 5.0 μm, essentially the same as for the 95-μm sample, decreasing to 3.0 μm for the 16-μm sample, a plausible trend. Most importantly, the frequency doubling at lower fields is much less pronounced in the 38-μm sample, and it is absent in the 16-μm sample. Evidently, the occurrence of fractional periods is an array width effect. It is this occurrence of fractional-quantum periods, and its array width dependence, that is the principal topic of the remainder of this paper.

As stated earlier, flux quantization effects are a fundamental feature of arrays of JJ's, and resistance oscillations with the canonical flux quantum period have been frequently reported, with most of the reports being on *two*-dimensional arrays of Josephson *tunnel* junctions.[7] Of particular interest in our context is the 1983 work of Webb *et al.*,[10] who were the first to report a strong oscillation component with one-half the canonical period, a phenomenon they attribute to ''the formation of a commensurate superlattice with alternating cells of N and $N+1$ flux quanta.'' Similar fractional oscillation periods in the magnetoresistance of two-dimensional (2D) arrays of Josephson tunnel junction have subsequently been reported repeatedly; a particularly dramatic example was seen by van der Zant *et al.*,[11] who found very sharp resistance minima also for half-integer values of the average number of vortices per cell, and they found less pronounced resistance minima for various *rational* fractional cell occupancies.

However, while there can be little doubt that the basic physics underlying the oscillations in our grating arrays is the same as in the 2D JJ arrays studied in the literature cited, there are significant differences in detail: Our arrays lack the *built-in* periodicity *across* the current flow that is present in the 2D arrays. Hence a more valid comparison would be with simple pairs of long JJ's, as have been studied, both theoretically and experimentally, by several authors, especially by Grønbech-Jensen and Samuelsen[12] (GJS) and by Ustinov *et al.*[13] These studies have shown that, in a stack of two closely interacting long Josephson tunnel junctions a vortex pattern evolves in which the vortices in the two junctions are staggered relative to each other, as a result of their mutual repulsion. Although the work cited pertains to simple pairs of JJ's, such a stagger between alternating cells should also be present in periodic arrays of *many* long JJ's, in which case resistance oscillations with one-half the canonical period might be expected. In fact, these considerations should apply, at least qualitatively, to artificial or natural periodic stacks of superconducting layers alternating with normal or insulating layers, including such extreme cases as the natural layer structure of bulk $YBa_2Cu_2O_{7-\delta}$ (YBCO). In fact, Ling *et al.*[14] have recently reported resistance oscillations in YBCO that have a magnetic period corresponding to a plane spacing close to twice the c-axis lattice constant of YBCO (1.16 nm).

In order to appreciate better the ease with which such a vortex superlattice might form in wide grating arrays such as ours, it is useful to consider a phenomenon first discussed in a classical 1967 paper by Owen and Scalapino[15] (OS). Those authors showed that long JJ's—even single ones—do not exhibit the simple ''textbook'' Fraunhofer diffraction pattern of the critical current for narrow junctions, which has nulls whenever the threading flux Φ is an integer multiple of the superconducting flux quantum Φ_0. Instead, the self-field of the Josephson currents drastically deforms the pattern and—more importantly—the set of equations governing the spatial distribution of magnetic flux and electrical current has multiple solutions: For any specified value of the *external* magnetic field, there are (at least) two different modes with distinctly different flux distributions, each characterized by quantized vortices, but with different spatial arrangements. For a *single* long JJ, the mode that should actually be present should be the one with the lowest free energy, that is, the mode having the highest critical current at that particular value of the magnetic field.

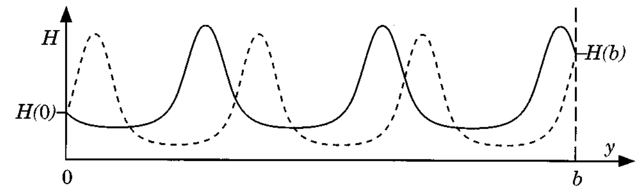

FIG. 5. Example (schematic) of two different magnetic-field distributions (Owen-Scalapino modes) with staggered vortices and slightly different vortex densities, but belonging to the same externally applied H field $H_e=\frac{1}{2}[H(b)+H(0)]$ and—in the case shown—carrying the same current $I=[H(b)-H(0)]w$ (SI notation). In general, the fields at the edges will not be the same for the two different modes, and the modes may carry different currents.

Consider, now, not a single long JJ, but a grating *array* of such junctions. In this case, the mutual repulsion energy of vortices will favor an arrangement in which the vortices in adjacent grating cells do *not* occur at the same position across the width of the grating. This would be true already in the absence of multiple Owen-Scalapino modes, but the existence of such modes will greatly facilitate the formation of such an arrangement, in which adjacent cells will belong to different OS modes (Fig. 5). That will be true especially if the overall magnetic field is sufficiently weak that the separation between the vortices within a given cell is large compared to the spacing a of the cells themselves. With increasing applied magnetic field, the two different modes will eventually be replaced by two new modes, but the fields at which the mode switches occur will be different for the different modes. During each mode switch, the flux contained in the affected cells will increase by Φ_0, but with only half the cells being affected, this corresponds to an *average* flux change by $\Phi_0/2$, and there will be two mode switches for every increase in the average flux per cell by Φ_0. Presumably, the resistance oscillations reflect those mode switches, thus providing a natural explanation for the frequency doubling of the resistance oscillations at low applied fields.

At high fields, the spacing between vortices within the *same* cell decreases, which reduces the energy that can be gained by forming an alternating-mode pattern. Our data suggest that this takes place at a vortex spacing around 10 μm. It can be shown that in the limit of sparse vortices, the peak of the field distribution near the center of the vortex can be approximated by a Lorentzian, with a full width at half magnitude $\Lambda=\sqrt{8}\lambda_J$. For our parameters, Λ

$=6.4\ \mu$m, implying a disappearance of the frequency doubling when the vortex separation approaches about 2Λ, at which point there is a significant overlap between adjacent vortices. A *quantitative* comparison between our data on the disappearance of the frequency doubling and our Λ estimate of 6.4 μm would require modeling along the lines of the work of GJS; it was not attempted. The disappearance of the half-period oscillations in narrow arrays is believed to have basically the same cause as their disappearance in wide arrays at high fields.

Note, finally, that the oscillation amplitude increases with decreasing cell size, but with a much more rapid attenuation per cycle. This, too, is a change to be expected: For short junctions, the multiple OS modes do not exist, each individual JJ should exhibit the classical Fraunhofer diffraction pattern of the critical current, and in a series connection of many such junctions, the sharp nulls of the single-junction pattern should get filled in and broadened by cell-to-cell variations and intercell coupling effects, leading to a resistance pattern close to that observed.

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