Measurements of Δ and v_F from Andreev reflections and McMillan-Rowell oscillations in edge junctions of $YBa_2Cu_3O_{6.6}/YBa_2Cu_{2.55}Fe_{0.45}O_y/YBa_2Cu_3O_{6.6}$

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We report measurements of dynamic resistance of high quality oxygen deficient SNS edge junctions with $YBa_2Cu_3O_{6.6}$ ($T_c=60$ K) as the superconductor (S) and $YBa_2Cu_{2.55}Fe_{0.45}O_y$ as the barrier (N). Below the gap a series of peaks in the dynamic resistance is identified as due to multiple Andreev reflections in the barrier ($V_n=2\Delta/en$), while above the gap, the peaks are attributed to McMillan-Rowell oscillations ($\Delta V=hv_F'/4ed_N$). Analysis of the subgap series in the 60 K $YBa_2Cu_3O_{6.6}$ yields a gap value Δ_{a-b} of 16 ±1.5 meV, and a coupling constant $2\Delta/kT_c$ of 6.2 ± 0.5. The McMillan-Rowell series yield the renormalized Fermi velocity of quasiparticles in the barrier $v_F'=(1.5\pm0.1)\times10^7$ cm/sec. [S0163-1829(99)15233-0]

Tunneling spectroscopy in NIS or SIS junctions is an important tool in the study of the high-T_c superconductors. It can yield the density of states of the superconductor, the symmetry of the order parameter, and other physical constants of the superconductor such as the gap energy and the Fermi velocity. A model of quasiparticles tunneling based on the Andreev reflection process was introduced by Blonder, Tinkham, and Klapwijk (BTK).[1] This model has been very successful in explaining tunneling results in junctions with low-T_c superconductors which have isotropic *s*-wave symmetry.[2] More recently, this model was extended by Tanaka and Kashiwaya to include anisotropic *d*-wave superconductors.[3,4] Experimental results of scanning tunneling microscopy (STM) and point contact spectroscopy were found to be consistent with the predictions of this extended model.[5,6] However, additional important physical properties can be obtained from the investigation of SNS junction. Recently, we observed geometrical resonances in the dynamic conductance of this kind of junction, which were attributed to Tomasch oscillations in one of the superconducting electrodes (the S layer).[7] This indicates that the interfaces in our edge junctions are sufficiently smooth to allow for the observation of this kind of interference effect.

In the present study we continued to investigate the dynamic resistance of our SNS edge junctions with barriers of different thickness and properties. This time, we focus on geometrical resonances in the *barrier* of the junctions (the N layer). In these junctions the incoming and reflected quasiparticles at each of the NS interfaces, or the bare S surface, are interfering and producing multiple Andreev reflections below the gap, or McMillan-Rowell and Tomasch oscillations above the gap.[8–10] It should be noted here that generally a junction shows either Tomasch oscillations, multiple Andreev reflections, or McMillan-Rowell oscillations, depending on its specific parameters such as the barrier strength and thickness. In the multiple Andreev scattering process, an incoming electronlike quasiparticle is reflected from one of the NS interfaces as a holelike quasiparticle with an opposite momentum. The holelike quasiparticle can then undergo Andreev reflection from the other SN interface as an electronlike quasiparticle, and so on. In every reflection process the quasiparticle gains an energy eV, where V is the voltage across the junction. Whenever the total energy gained by the quasiparticle reaches twice the gap energy 2Δ, it makes an interference process which leads to a peak in the dynamic resistance at $V_n=2\Delta/en$, where n is the number of reflections that the quasiparticle has gone through.[8,11] The multiple Andreev phenomena, also called subharmonic gap structures in the literature, was observed in the past in the dynamic resistance of low-T_c junctions with smooth interfaces.[12–15] Recently, similar series of peaks (with $n=1$ and 2) have also been observed in high-T_c edge junctions and attributed to a peculiar SNcNS structure.[16] Quasiparticles in the barrier with energies above the gap can also be reflected from the interfaces and produce interference effects. This yields series of peaks (or resonances) in the dynamic resistance, which are known as McMillan-Rowell oscillations.[10,17] The period of these oscillations is equal to $hv_F'/4ed_N$, where v_F' is the renormalized Fermi velocity in the barrier, and d_N is the thickness of the barrier. In the present study we investigate geometrical resonances in the dynamic resistance as described above, in oxygen-deficient edge junctions with $YBa_2Cu_3O_{6.6}$ ($T_c=60$ K) electrodes. We observed subharmonic gap structures due to Andreev scattering up to $n=5$, and found the energy gap Δ and the coupling constant $2\Delta/kT_c$. Above the gap, we observed linear series of peaks in the dynamic resistance up to $n=18$ which were identified as McMillan-Rowell oscillations that also yield v_F' in the barrier.

We prepared oxygen-deficient edge junctions with $YBa_2Cu_3O_{6.6}$ ($T_c=60$ K) as the superconductor and $YBa_2Cu_{2.55}Fe_{0.45}O_y$ as the barrier.[7] This barrier in the well-oxygenated phase has a $T_c^{onset}\approx10$ K, while in its oxygen-deficient phase it shows localization with resistivity $\rho(4$ K) of about 10 $m\Omega$ cm. A schematic diagram of the junction is shown in Fig. 1. The fabrication process is described in detail elsewhere.[7] Briefly, the base electrode and insulator layers were deposited by laser ablation deposition on a 10 $\times10$ mm^2 wafer of (100) $SrTiO_3$. Then using a waterless deep UV photholigraphy process, the edge was made by Ar ion milling at an angle of $\alpha=36°$. After this, a second deposition run was carried out, in which a barrier, a cover elec-

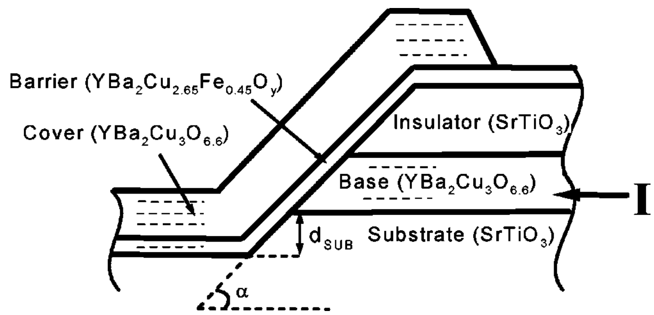

FIG. 1. A schematic diagram of an edge junction used in the present study.

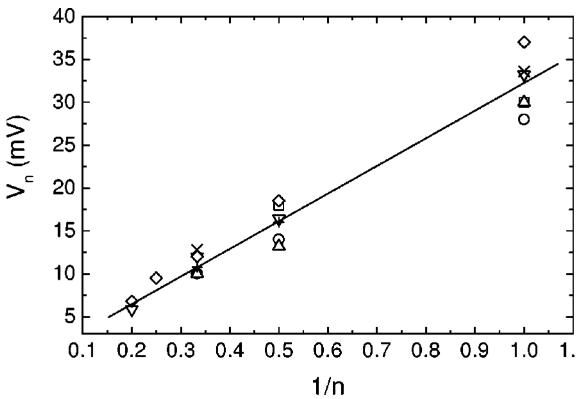

FIG. 3. V_n of the dV/dI peaks at 4 K of seven junctions as a function of $1/n$.

trode, and gold contact layers were prepared. The sample was then cooled down in oxygen flow ambient of 40 mTorr to obtain the 60 K phase. Finally, the sample was patterned into ten junctions, each of 5 μm width. The thicknesses of the base, barrier, and cover layers were 70, 15, and 70 nm, respectively. Our junctions have a full epitaxial structure, with good coupling along the *a-b* plane. We have already observed geometrical resonances in this kind of junction,[7] and demonstrated our ability to control their geometry and conductance properties.

The dynamic resistance dV/dI of the junctions at 4 K was measured by *direct* differentiation of the I-V curves using ac current modulation dI and a lock-in amplifier for the detection of dV. A typical result is shown in Fig. 2. One can easily see that the junction has a weak link behavior of the SNS type with resonant peaks superposed on it. We note that in this figure the intensities of the odd number peaks are higher than those of the even number peaks, and also that there are steplike structures in this spectrum. These effects, however, are coincidental since in other junctions they are absent. For the peaks near $V=0$ we could not obtain a systematic picture, and possibly these peaks can be attributed to various bound states. The inset to Fig. 2 shows that the voltage values V_n of these peaks are proportional to $1/n$, where n is the peak number and V_n is half the distance between the plus and minus nth peaks. We observed similar series of subharmonics peaks in seven out of ten junctions on the same wafer

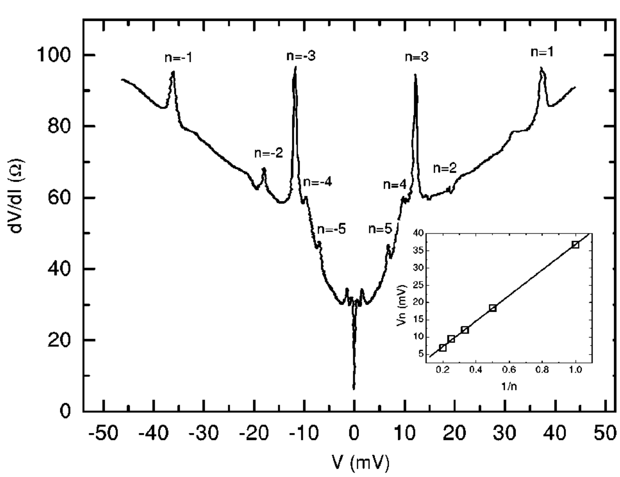

FIG. 2. Dynamic resistance dV/dI at 4 K of an $YBa_2Cu_3O_{6.6}/YBa_2Cu_{2.55}Fe_{0.45}O_y/YBa_2Cu_3O_{6.6}$ edge junction. In the inset, V_n of the peaks at 4 K are plotted as a function of $1/n$.

and the results from all the seven junctions are shown in Fig. 3. This figure shows that V_n is linear in $1/n$ as expected from the simple theoretical expression for the subharmonic gap structure:[8]

$$V_n=\frac{2\Delta}{en}, \tag{1}$$

where n is an integer. Fitting of the data in Fig. 3 to Eq. (1) yields $\Delta_{a-b}=16\pm1.5$ meV and a coupling constant $2\Delta/kT_c$ of 6.2 ± 0.5. Previously, gap values in the range of 15–18 meV with a coupling constant of 6.1–7.0 were measured in SIS break junctions in single crystals of $YBa_2Cu_3O_{6.6}$ ($T_c\approx57$–63 K).[18,19] Our results of the energy gap value and the coupling constant measured from multiple Andreev reflections are therefore in full agreement with the values found in the SIS break junctions in the tunneling regime. Our energy gap value is also consistent with the Andreev gap measured by the point contact method in an underdoped $YBa_2Cu_3O_{6.6}$ film ($T_c\approx66$ K and $\Delta=13$ meV).[20] It is, however, in complete disagreement with the tunneling results of the same group in NIS junctions where a gap value of 50 meV ($T_c\approx60$ K) was found.[21]

In some of our junctions with steeper edge slope ($\alpha=50°$) and voltages above the gap, we found series of peaks in the dynamic resistance that have a constant periodicity. This is expected to occur if these peaks are due to either Tomasch oscillations at energies significantly higher than the gap or McMillan-Rowell oscillations. The voltages of the peaks due to the Tomasch oscillations are given by[22]

$$eV_n=\sqrt{(2\Delta)^2+\left(\frac{nhv'_{FS}}{2d_S}\right)^2}, \tag{2}$$

where Δ is the gap, v'_{FS} is the renormalized Fermi velocity in the superconductor, and d_S is the thickness of the superconductor. The voltage spacing between the peaks of the McMillan-Rowel oscillations is[10]

$$\Delta V=\frac{hv'_{FN}}{4ed_N}, \tag{3}$$

where v'_{FN} is the renormalized Fermi velocity in the barrier, and d_N is the thickness of the normal barrier (see Fig. 1). In order to distinguish between the Tomasch and McMillan-Rowell oscillations, we had prepared two kind of junctions

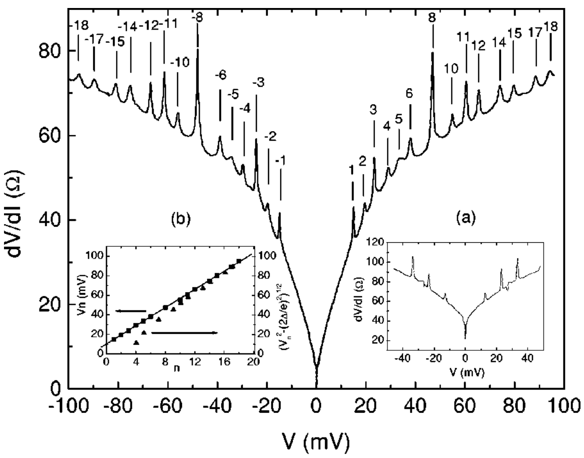

FIG. 4. Dynamic resistance dV/dI at 4 K of an $YBa_2Cu_3O_{6.6}/YBa_2Cu_{2.55}Fe_{0.45}O_y/YBa_2Cu_3O_{6.6}$ edge junction, with a barrier thickness $d_N=30$ nm. In inset (a), d_N is 15 nm. In inset (b), V_n (squares) and $\sqrt{V_n^2-(2\Delta/e)^2}$ (triangles) of the peaks in the main panel are plotted as a function of n.

with different barrier thickness of 30 and 15 nm on two wafers. On each wafer we had ten junctions, and typical dynamic resistance spectra of two representative edge junctions one from each wafer are shown in the main panel and in inset (a) of Fig. 4. Equations (2) and (3) show different scaling of the periodicity of oscillations with the thicknesses d_N and d_S. The voltage spacing ΔV between the peaks in the main panel is 5 mV ($d_N=30$ nm), which is about half that seen in inset (a) to Fig. 4, 10 mV ($d_N=15$ nm). From Eq. (2) one can see that $\sqrt{V_n^2-(2\Delta/e)^2}\propto n$, while from Eq. (3) it follows that $V_n\propto n$. In inset (b) to Fig. 4 we plot these two dependences using our data of V_n from the main panel of this figure and $\Delta=16$ meV which we had already found before. One can see that $\sqrt{V_n^2-(2\Delta/e)^2}$ is not linear in n as predicted by Eq. (2) and this result rules out the possibility that the observed resonances are due to Tomasch oscillations. Clearly, $V_n\propto n$ as can be seen from the straight line in inset (b) to Fig. 4. Thus Eq. (3) describes our results best, and therefore the observed resonances are due to McMillan-Rowell oscillations in the barrier. The slope of the line in inset (b) to Fig. 4 yields ΔV as in Eq. (3) from which the renormalized Fermi velocity of the Fe-doped YBCO barrier can be calculated. Using these data and also V_n versus n from the data of inset (a) to Fig. 4 (not shown), we find that $v'_{FN}=(1.5\pm0.1)\times10^7$ cm/sec. Previously, we measured in similar edge junctions the renormalized Fermi velocity in $YBa_2Cu_3O_{6.6}$ junctions from Tomasch oscillations, and found $v'_{FS}=(4.4\pm0.2)\times10^7$ cm/sec which is quite reasonable for the pure material.[7] Thus, in our junctions, the ratio r between the Fermi velocities in S and N is about 3. In principle, r can be calculated for different values of the effective barrier strength Z_{eff} in the junctions from the relation $Z_{eff}^2=Z^2+(1-r)^2/4r$ where Z is the actual barrier strength.[2] In order to estimate Z_{eff} we use our results in similar junctions with thicker barriers. In these junctions, tunneling behavior was observed in the dynamic conductance such as in SIS junctions. This conductance was found to be consistent with the extended BTK model for d-wave superconductors,[3,4] and from preliminary fits to this model we found that the effective barrier strength Z_{eff} is about 1 in these SIS junctions. For the SNS-type junctions in the present study (with thinner barriers) we shall assume $Z_{eff}\approx0.5$. If we also take the actual Z value as 0.1 (close to zero), we find that $r\sim2.6$, which is in reasonable agreement with the experimentally measured value of about 3.

In summary, our results show clearly the different series of geometrical resonances, mainly because of the well-defined geometry and the smooth interfaces in our edge junctions. The dynamic resistance of our edge junctions showed SNS-type characteristics with sharp series of peaks superposed on it. Below the gap, these resonant peaks were identified as subharmonic Andreev scattering, which yield a gap value of $\Delta_{a-b}=16\pm1.5$ meV and a coupling constant $2\Delta/kT_c$ of 6.2 ± 0.5. Above the gap, we observed McMillan-Rowell oscillations which yield a renormalized Fermi velocity in the barrier of $(1.5\pm0.1)\times10^7$ cm/sec.

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