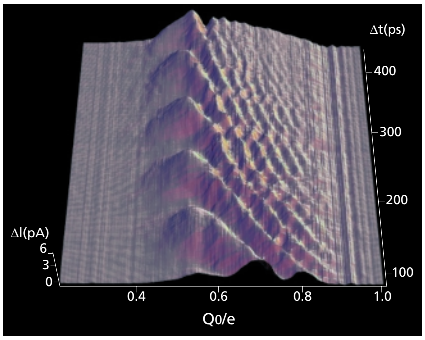
Younger Scientists

Yasunobu Nakamura

The JSAPI would like to introduce to you Mr. Yasunobu Nakamura, who won the Young Investigator Award at the 1999 Japan Society of Applied Physics Fall Meeting for the outstanding quality of his research. Mr. Nakamura is an assistant manager in the NEC Fundamental Research Laboratories working on the quantum-state control of nanoscale superconducting devices.

There come exciting moments in every researcher's life when he or she wants to cry out, "I've found it!" In my case, the most recent and biggest experience of this kind was when I saw a particular oscillating signal (see figure) on the monitor of our PC in the lab. The oscillation corresponded to the coherent time evolution between two quantum states in a mesoscopic superconducting device known as a Cooper-pair box.[1] This result demonstrated, for the first time, the coherent control of quantum states of an artificial two-level system in a solid-state device. I was able to reach this goal, which is a preliminary step towards quantum computing, because of a number of lucky encounters in the course of my career.



When I first joined the NEC Fundamental Research Laboratories eight years ago, I started to study single-electron tunneling devices with Dr. Jaw-Shen Tsai, who has been my boss and co-worker ever since. That was five years after Fulton and Dolan of Bell Laboratories had first demonstrated the feasibility of a single-electron transistor (SET).

The operation of SETs at that time was still limited to temperatures below 1 K because the single-electron charging energy of the island electrode coupled to the source and the drain via small tunnel junctions was so small. We therefore tried to make the island smaller. By using electron-beam lithography and an anodization technique to fabricate an island of 20 nm in size, we succeeded in raising the operating temperature to about 100 K. (We have recently achieved operation at room-temperature.[2])

Naturally, since the Al electrodes (which we also use in larger devices) become superconducting below about 1 K, the temperature range in which we usually have to make measurements on these devices, we were also interested in researching the characteristics of a superconducting SET (S-SET). In superconducting electrodes, electrons form Cooper pairs which tunnel through junctions in a coherent manner by means of the Josephson effect. The coherent superposition of two charge states, differing by just one excess Cooper pair in the island (or 'box'), thus becomes possible in an S-SET.

My first naïve question was how we could obtain directly observed evidence of the superposition. My interest stemmed from the duality of the Cooper-pair box and the SQUID ring, in which macroscopic quantum coherence between two flux states has long been sought. I had already learned that in quantum mechanics a coherent two-level system would lead to the formation of two eigenstates with symmetric and antisymmetric wave functions, and coherent oscillations in the time-domain between the two localized states. But how could we make those eigenstates or oscillations visible?

In earlier experiments on the I-V characteristics of S-SETs, I had noticed that an S-SET can be regarded as a combined Cooper-pair box and voltage-biased probe junction in certain conditions. Although it is difficult to observe clear evidence of coherent superposition through dc I-V measurements, the concept of detecting the charge states from the tunneling through the probe junction turned out to be very useful in later experiments.

The first good idea came from what seemed initially to be an unrelated paper about semiconductor coupled quantum dots by Stoof and Nazarov of Delft University of Technology. The authors had proposed using photon-assisted tunneling as a spectroscopic tool to study the energy-level splitting between two coherently coupled states. On reading the paper, I immediately drew an analogy with the S-SET problem and started an experiment in which I irradiated samples with microwaves. The experiment successfully showed clear level-anticrossing due to the superposition of two charge states.[3]

Having obtained evidence of coherence, the next question was how long the coherence could be maintained. In principle, a line-width analysis of the photon-assisted peak could provide some information about decoherence. However, it was hard to measure in practice the expected very sharp peak width without extrinsic broadening due to experimental fluctuations. Hence, I felt that a time-domain experiment to observe the coherent oscillations was necessary.

The problem was that the time-scale of the oscillation in our device was typically only 100 ps. This appeared to be too fast for good control by an electric voltage pulse transmitted from a room-temperature instrument to a device embedded in the cryostat. I happened to hear, though, that one of my colleagues in the same group had succeeded in delivering 10 GHz digital signals to a circuit in his cryostat, so I adopted his technique and carefully designed an experimental set-up. At the very first trial, that resulted in more beautifully defined observations of oscillating signals from the quantum-state evolution than I had dared expect.

In the last five years or so, quantum information technology has become a very popular field of study and the Cooper-pair box is now considered a candidate for use as a quantum bit. Although I am still not sure to what extent we can push this and other technologies towards quantum computing, directly controlling and measuring the quantum state of a physical system is a new and challenging concept, particularly for solid-state devices. I hope to continue spending part of my time trying to unveil and visualize some of the important and interesting phenomena that lie hidden in this field of nature, while keeping in mind that *the Little Prince* said, "What is the most important thing is invisible..."

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References

1) Y. Nakamura, Yu. A. Pashkin and J. S. Tsai, Nature **398**, 786 (1999).
2) Yu. A. Pashkin, Y. Nakamura and J. S. Tsai, Appl. Phys. Lett. **76**, 2256 (2000).
3) Y. Nakamura, C. D. Chen and J. S. Tsai, Phys. Rev. Lett. **79**, 2328 (1997).

Nakamura received his BS degree from the Department of Applied Physics in the University of Tokyo, and received his Master's degree, majoring in high-Tc superconductivity research, from the same university. He joined the NEC Fundamental Research Laboratories in 1992 and was awarded the Nishina Memorial prize and the Sir Martin Wood prize in 1999.