Carrier capture dynamics at localized gap states of Co nanoparticles grown on GaAs(110) probed by time-resolved STM

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Localized gap states in semiconductors, which originate from defects, impurities, and adsorbates, affect the carrier dynamics dramatically through capture, emission, and recombination processes. Considering control of carrier dynamics, the localized gap states are sometimes problem to be avoided and sometimes useful to design ultra-fast semiconductor devices. With the recent development of semiconductor nanotechnology, it became important to probe and understand the carrier dynamics around localized gap states with high spatial resolution. In this study, we have visualized the carrier capture dynamics around gap states artificially formed on GaAs, using shaken pulse-paired excited scanning tunneling microscopy (SPPX-STM) [1].

In an SPPX-STM measurement, the tunnel gap of STM is illuminated by a sequence of paired pulses and the corresponding change in tunneling current ΔI is measured as a function of delay time between the paired pulses (t_d). The decay time of the photocarriers due to the surface recombination can be estimated from the dependence of the ΔI against delay time. Cobalt nanoparticles were grown on GaAs(110) (n-type, Si-doped $1 \times 10^{17} cm^{-3}$) surface to generate localized gap states deep in the GaAs bandgap.

STM images on Co/GaAs reveal that the Co nanoparticles are well isolated and almost the same in size (Fig. 2). Figure 3 shows ΔI vs. delay time curves obtained (a) above bare GaAs surface and (b) above a single Co nanoparticle that associates with the gap state. As expected, the decay constant above Co, 2.3 ns, is shorter than that above the bare GaAs surface, 220 ns due to the high recombination rate at the gap state. We found,

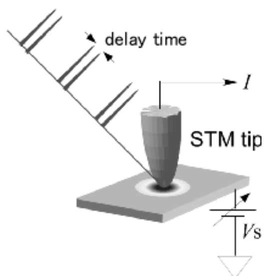


Fig. 1 Schematic of SPPX-STM measurement.

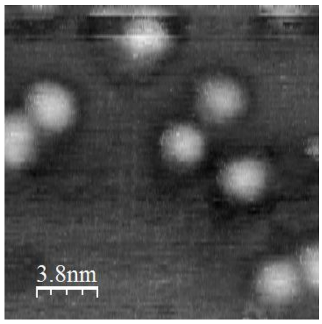
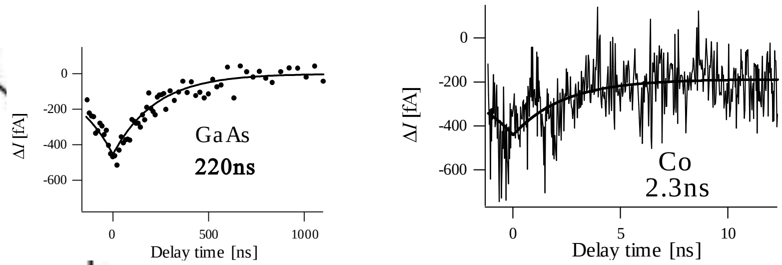


Fig. 2 STM topography Co/GaAs

however, that the apparent lifetime of the surface photocarriers are dependent on the magnitude of the tunnel current. We interpreted the fact as following. The minority photocarriers (holes in this case) that is excited in the depletion layer drift towards the surface under the bias voltage. There, the electrons (counter carriers) are depleted and, therefore, regardless of the existence of the gap states, no recombination occurs without tunnel current. In our experiment, the counter carriers are provided from the STM tip via tunneling as illustrated in Fig. 4. Above a Co particle, accumulated holes are trapped by the gap state, and recombine with the electrons tunneling from the STM tip (Fig. 4(b)). Assuming that electrons and holes encountered at the gap state recombine immediately, carrier recombination rate at Co a nanoparticle is determined by the relationship between the injection rate of tunneling electron to a gap state (J_e) and the capture rate of minority holes (J_h). Based on this physical model, we derive the hole capture rate (J_h) of single Co particles and discuss its relationship to the particle size.

(a) (b)



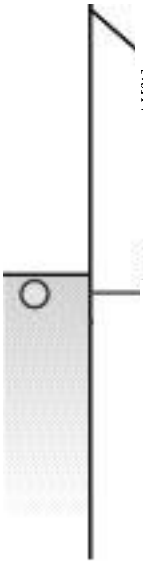


Fig. 3 ΔI vs. delay-time curve obtained above (a) bare GaAs (b) Co/GaAs

(a) (b)

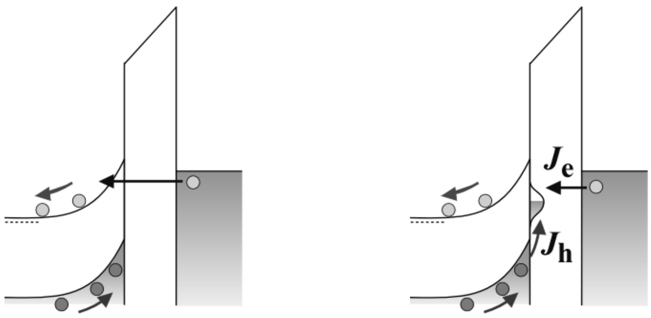


Fig. 4 1-D energy band diagram of tunnel junction
(a) bare GaAs (b) Co/GaAs

References

[1] Y. Terada, M. Aoyama, H. Kondo, A. Taninaka, O. Takeuchi and H. Shigekawa, Nanotechnology **18**, 44028 (2007).