photon emission data [26]. From Eq. (4) and $R_{h\nu} = \eta I_0 P$, we can derive

$$\frac{dR_{h\nu}}{dV_b} \approx \frac{1}{w_e\left(V_b\right)}\left[\eta I_0 \rho_s\left(eV_b - h\nu\right) - R_{h\nu}\rho_s\left(eV_b\right)\right]. \tag{7}$$

Hence, the derivative of photon emission rate with respect to bias voltage can be used to trace back the DOS characteristics of the sample under the condition that the tip possesses a slowly varying DOS distribution. As an example, we plot an arbitrary DOS distribution shown by the upper curve in Fig. 4(a). The calculated photon rate $R_{h\nu}$ with $h\nu = 1.7$ eV is drawn by the middle curve according to Eq. (4). The lower curve gives d$R_{h\nu}$/dV_b. From Eq. (7), the positive peaks in d$R_{h\nu}$/dV_b are corresponding to IET channels at energy of $eV_b - h\nu$, while negative dips are associated with ET channels at energy of eV_b. Therefore we can assign the three positive peaks in d$R_{h\nu}$/dV_b to the electronic states A, B and C, which are 1.7 eV down-shifted, and the negative dip to state D at the same energy. Figure 4(b) shows the derivative data of d$R_{h\nu}$/dV_b (up and down triangles) measured at the cluster before and after manipulation (the marked cluster in Fig. 3(a)) towards the dI/dV_b spectra, where the d$R_{h\nu}$/dV_b data are downshifted by the photon energy of 1.9 eV. The d$R_{h\nu}$/dV_b data nicely reconstruct the characteristic local electronic states revealed by STS spectra. Figure 4(c) shows the derivative data of d$R_{h\nu}$/dV_b measured on CuN as compared with its dI/dV_b spectrum. The negative dip in d$R_{h\nu}$/dV_b is associated with the 2.3 V peak in the DOS of CuN.

5. Conclusion

In summary, we have demonstrated that the TIP photon emission efficiency can be manipulated by controlling the IET and ET processes with local electronic states in a STM tunneling gap. With artificial nanostructures, we can either open or close the IET channel and thus enhance or suppress the plasmon excitation. The theoretical model taking into account the contribution of the local DOS agrees well with the experimental data. We'd like to emphasize that in this work we do not intend to provide a new description of the origin of the STM-stimulated photon emission; instead, we have formulated a relationship between local electronic states and the efficiency of TIP photon emission. This relationship is found to be general, which is rooted in the Fermi's golden rule, and independent of the origin of the electronic states or the tip structure. Moreover, this relation allows us to manipulate the photon emission efficiency through creating artificial electronic states. These results have demonstrated that experimentally-measured TIP photon emission efficiency can be quantitatively described by a theoretical formulation which computes ET and IET tunneling processes, providing useful guidance for designing and engineering nanophotonic devices in the subnanometer scale.

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