Plasmon excitation observed in quasi one-dimensional nanowires

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Abstract. We report the first cut of our study on the behavior of a plasmon excitation observed from quasi-one-dimensional (Q1D) metallic nanowires self-assembled on the Si(111) surface. We have utilized a high-resolution electron-energy-loss spectroscopy to measure the extremely anisotropic dispersions of the Q1D plasmon excitation. The energy-momentum dispersion $\omega(q)$ is well accounted by both theories with and without interactions, and thus provides no evidence for non-Fermi liquid properties. The $q$-dependence of life time of the plasmon, however, seems to exhibit a behavior distinct from that of Fermi liquid as predicted recently.

1. Introduction
Unlike higher dimensional electrons systems, electrons in one-dimensional (1D) systems are predicted to behave quite differently from that expected in the Fermi liquid theory. Such non-Fermi liquid properties may be characterized as the Luttinger liquid (LL) properties as predicted earlier [1]. Despite the increasing literature of evidence for LL behavior in numerous 1D systems, for example, carbon nanotubes [2, 3], anisotropic bulk materials [4, 5], dispute has been continued due essentially to the intrinsic instabilities of the 1D electrons systems and low energy nature of the excitations.

In/Si(111)-4×1 surface has been known as the quasi-1D metallic wires self-assembled on the Si(111) surface [6, 7, 8]. This system has been reported to have perfect nesting vector in the Fermi surface and to undergo a Peierls type metal-insulator transition upon cooling below $T_c=120$ K [9]. The well defined Q1D metallic nature of the In nanowires at room temperature may be a model system to find a clue for the non-Fermi liquid behavior of interacting 1D systems.

We have measured energy-momentum dispersions $\omega(q)$ of a plasmon excitation in the nanowires using high-resolution electron-energy-loss spectroscopy (HREELS) with energy resolution better than 3 meV. The dispersion $\omega(q)$ is found to follow the behavior exactly predicted by both a random-phase-approximation (RPA) for non-interacting electrons and the LL theory for the interacting electrons. This is not quite surprising since both theories predict the same $\omega(q)$ behavior in the long wave length limit. We note that both theories, however, become distinct on the dispersions of lifetime $\tau(q)$ of a low energy 1D excitation such as the low energy plasmon we observed.
2. Experimental Details
The HREELS system utilized is equipped with a Leybold-Heraeus ELS-22 spectrometer, which has an optimum energy resolution and the half-acceptance angle of the spectrometer can be 8 meV and 2 °. Our HREELS measurements have been performed under a base pressure below 7 x 10^{-11} mbar. Leybold spot-profile analysis low-energy-electron diffraction (SPA-LEED) has also been used to identify the clear In/Si(111)-4x1 surface.

A n-doped Si wafer with resistivity of ∼2 Ωcm was used to prepare a Si(111)-7x7 surface. We have resistively heated our sample up to 1200 °C for 10 seconds followed by annealing at 800 °C for 5 minutes to obtain the clean 7x7 phase. No detectable local vibrations for hydrogen, oxygen, and carbon assure the sample cleanness. Source deposition was performed by flowing current through a tungsten filament wrapping In piece. We have eventually obtained a single domain In/Si(111)-4x1 phase by annealing the In-adsorbed surface at about 400 °C. All measurements have been performed within 2 hours after cleaning the sample to avoid contaminations.

3. Result and Discussion
Figure 1 shows the EELS spectra obtained from the In/Si(111)-4x1 surface parallel(q∥) and perpendicular(q⊥) to the direction of nanowires. The fact that the characteristic loss peak L₁ is observed only along the direction parallel to the length of the wires demonstrates the anisotropic nature of the 1D dispersion. When each spectrum is fitted with a gaussian peak function after subtracting an inverse polynomial background, a relatively broad loss peak, L₂, is found. We have attributed L₂ to an interband excitation of electron-hole pair excitation between the surface bands m₁, m₂ and m₃ [9]. Since L₁ is seen only from the 4x1 surface not from the Si(111)-7x7 nor the In/Si(111)-√31x√31 surface, it is considered a characteristic loss peak due to the Q1D metallic nature of the system.

![Figure 1. HR-EELS spectra obtained from the In/Si(111)-4x1 surface along the direction perpendicular(q⊥), and parallel(q∥) to the length of the In nanowires. The spectra have been fitted with a Gaussian peak after subtracting a polynomial background. The characteristic loss peak L₁ observed only along the parallel direction is considered to be a unique feature of the Q1D metallic system. The loss peak L₂ seen in both directions is attributed to an interband transition between the surface bands reported earlier.](image-url)
One may think of several possible origins for a relatively sharp loss peak $L_1$ including an interband transition, a collective excitation such as plasmon or phonon, and a local atomic vibrational excitation. Other possibilities except the case of a plasmon excitation may be easily excluded because of the relatively broad linewidth ($\gtrsim 25$ meV) much broader than a typical line-width of local vibrational origin and the loss energy higher than Si optical phonons ($\sim 60$ meV). The absence of multi-phonon peaks further confirms that the $L_1$ is not a phononic excitation.

Properties of plasmon excitation in 1D system may be well described in terms of two theories, the RPA and the LL theory for the non-interacting and interacting iD electrons systems, respectively. Unfortunately both theories, however, predict exactly the same energy-momentum dispersion $\omega(q)$ in the long wave-length limit [10, 11].

$$\omega(q) = q|v_F^2 + \frac{2}{\pi\hbar}v_F V(q)|^{1/2},$$

where $V(q)$ is the fourier transformed 1D Coulomb potential, $v_F = \hbar k_F/m^*$ is a 1D Fermi velocity. By taking electron effective mass $m^*$ as a fitting parameter, we have compared our experimental data with theory. The dispersion $\omega(q)$ is found to be in excellent agreement with that of both theories for $m^*/m_e \sim 0.23$.

Despite of the Q1D feature of the In/Si(111)-4×1 surface, no clear evidence of non-Fermi liquid properties has been reported so far. The dispersion $\omega(q)$ found in this work also provides no evidence of non-Fermi feature because both theories for non-interacting and interacting are indistinguishable in the momentum range measured. Moreover no evidences of the LL behavior has been reported in previous photo-emission spectroscopy experiments [12]. However, non-symmetric band dispersion is predicted to bring about collision between spin and charge excitations, which may result in the bosonic mixed-spin-charge excitations in quasi-1D electrons system [13]. We note that three surface states on the surface are not symmetric to $\Gamma$ point. The difference between two Fermi wave vectors ($\delta v = |v_{F1} - |v_{F2}|$) provides a reasonable basis to account for non-LL like behavior.

We thus resort to other possible origin for the plasmon excitation we observed. As predicted earlier, non-Fermi liquid properties may be manifested by non-analytic $q$-dependence of lifetime of an elementary excitation when typical evidence such as spin-charge separation is severely suppressed [16]. The decay rate represented by the plasmon line-width (or inverse of its life time) of a volume plasmon for conventional metals such as Al is known to obey the quadratic dispersion on $q$ [14] while it becomes linear when exchange and correlation effects are taken into account [15]. However, we note a theoretical prediction that it has non-analytic dependence on $q$ such as $q^{1.5}$ for an ideal clean LL. Elementary excitations for an ideal electron gas, which have an infinite life-time, decay by the collisions from each other mainly due to non-linear band dispersion [16]. We have tried to find if this prediction may be applied to the In/Si(111)-4×1 surface despite of many non-ideal conditions imbedded in our sample.

Indeed our sample is a Q1D rather than an ideal 1D electrons system and contains extra interactions due to imperfections such as impurities, finite size, and finite temperature that may induce electron-phonon interaction, back scattering, and impurity scattering, and so on. The first cut of our data fitting suggests a possibility of non-analytic exponent of the life time of the plasmon observed from the metallic nanowires of the In/Si(111)-4×1 surface. More elaborate fitting process is underway to quantify the exponent. Our conclusive results will be reported elsewhere [17]. Because of increased density of electrons in the nanowires, we anticipate to find a non-analytic exponent for the lifetime of the plasmon excitation despite the existence of many non-ideal conditions.
4. Summary
We have studied a characteristic excitation, plasmon, of the metallic nanowires formed in the In/Si(111)-4×1 surface focussed on the q-dependence of its energy $\omega(q)$ and the lifetime $\tau(q)$. No clear evidence of non-Fermi liquid properties has been found from $\omega(q)$ since both theories RPA and Luttinger theory of non-interacting electron gas and interacting electrons system predict the same behavior. Attempt to find a non-analytic exponent for $\tau(q)$ with improved accuracy, however, is underway to prove if the metallic nanowires indeed exhibit any non-Fermi liquid behavior as recent theory predicts.

5. References
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