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Florent Perez, Bernard Jusserand, Claus Dahl, Marcel Filoche, Laurence Ferlazzo-Manin, et al..  
Folded and confined one-dimensional plasmons in modulated wires. Superlattices and Microstructures, 1997, 22 (2), pp.257-260. 10.1006/spmi.1996.0346 . hal-02442495

**HAL Id: hal-02442495**

**<https://hal.science/hal-02442495>**

Submitted on 27 Nov 2022

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## Folded and confined one-dimensional plasmons in modulated wires

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(Received 15 July 1996)

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We demonstrate theoretically and experimentally that one-dimensional plasmons of doped wires are either extended or longitudinally confined when the lateral width of the wires is periodically modulated. Theoretical dispersion curves, calculated within a classical framework, reproduce well the experimental dispersion deduced from Raman scattering on deep etched modulated wires. Zone-edge gap openings, increasing with the modulation amplitude, are exhibited. We show that deep etching allows a good control of complex geometries and provides quasi-abrupt boundary conditions.

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**Key words:** GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As, low dimensional electron gases, quantum wires, plasmon, reactive ionic etching.

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### 1. Introduction

Advances in the microfabrication techniques of semiconductors have given access to devices with one-dimensional (1D) confinement of electrons. The plasmon dispersion is a very sensitive probe for important physical parameters of these devices such as the electron density distribution and the electrostatic confinement potential [1].

In this communication, we present an experimental and theoretical determination of the plasmon dispersion in wires with a strong periodic modulation of the lateral size along the wire axis. We describe a numerical solution for the plasmon dispersions in laterally confined 2D electron systems and compare with those, which we have measured by Raman scattering on deep-etched modulation-doped GaAs quantum wells. The study clearly evidenced new behaviors for the plasmon modes, reflecting the longitudinal modulation and the long-range character of the Coulomb interaction.

### 2. Experiment

We have fabricated modulated wires by deep reactive ion etching of a GaAs/GaAlAs modulation-doped single quantum well, followed by an anodic oxidation [2], with a process identical to the one already described in Ref. [1] for the fabrication of unmodulated wires. We have realized arrays of 160 parallel, 1- $\mu$ m-spaced,

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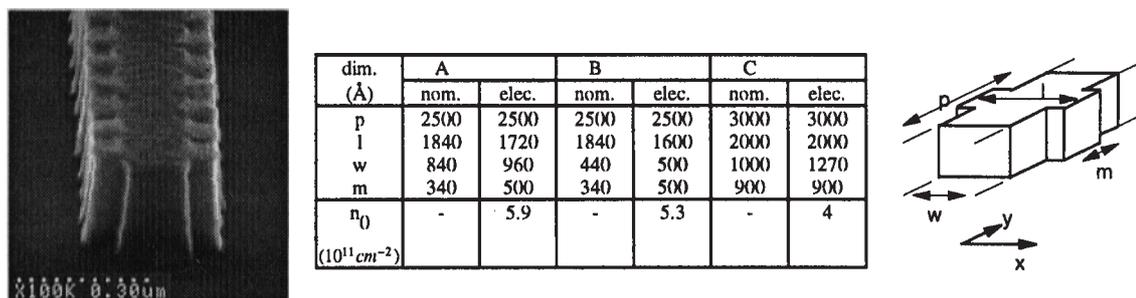


Fig. 1. The left part shows an SEM micrograph of sample A. Definition of geometrical parameters, nominal values and electrical ones deduced from the fit are given for samples A, B, C.

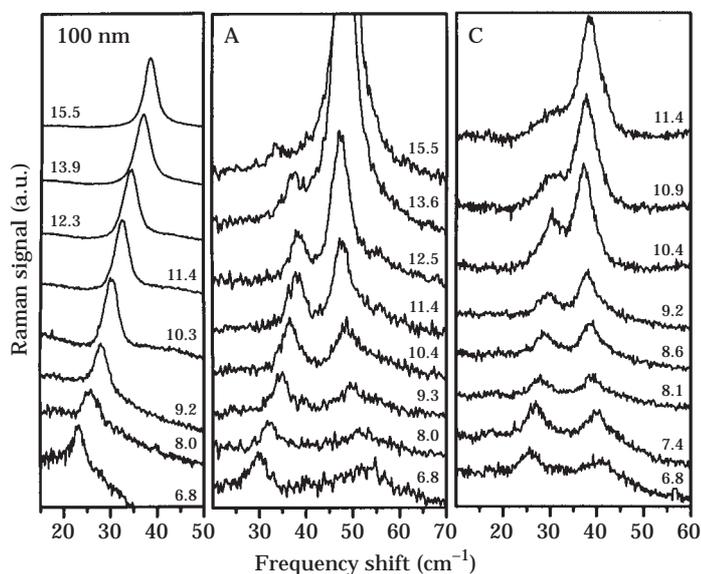


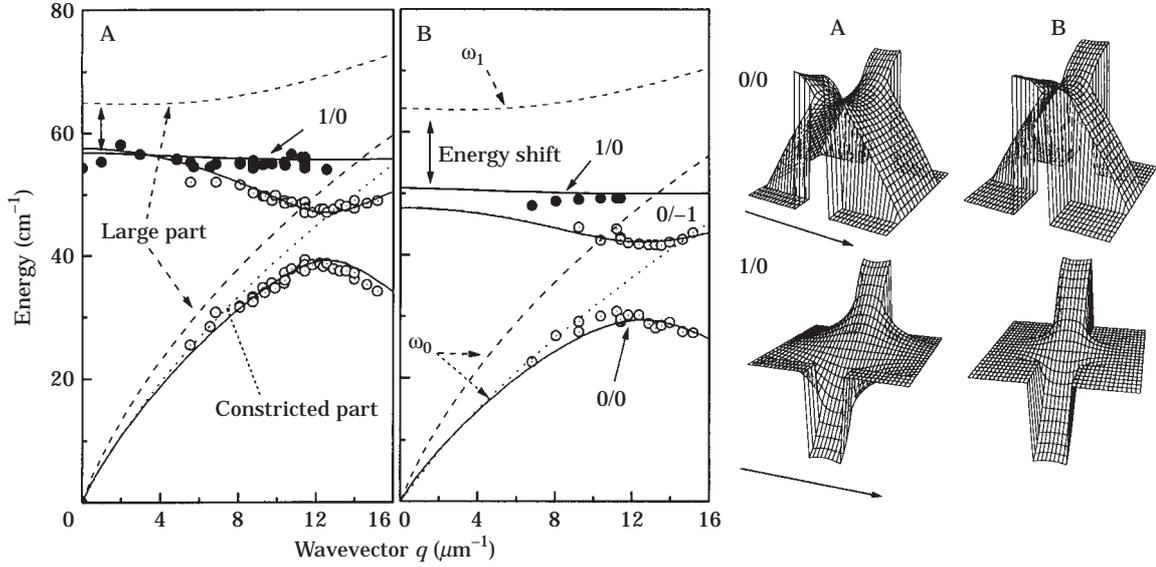
Fig. 2. Three sets of Raman spectra with only the lowest even mode taken respectively, from left to right, on a  $1000 \text{ \AA}$  width unmodulated wire and on sample A and C.

$160 \mu\text{m}$ -long periodically modulated wires. Three different arrays have been realized in order to investigate both a change in the modulation amplitude at fixed period (sample A and B) and a change in the modulation period with close modulation amplitude (sample A and C). Figure 1 shows a scanning electron microscopy photography (SEM) which illustrates the good definition of the modulated profile. We give also a table with the nominal parameters  $p$ ,  $l$ ,  $w$ ,  $m$  and their definitions, corresponding to each sample A, B, C.

We have determined nominal  $p$ ,  $l$ ,  $w$ ,  $m$  according to the method developed in Ref. [1] for unmodulated wires; the coded width was corrected from the oxide thickness (48 nm on each surface).

Raman quasi-backscattering experiments have been performed in pumped liquid helium with an incident laser energy (1.59 eV) in the same conditions as in Ref. [1].

Figure 2 compares Raman spectra obtained on a unmodulated wire with ones obtained on sample A and C. Only the lowest even mode is shown. It clearly demonstrates the modification brought by the modulation: a gap opening whose position is at wavevector  $q = \pi/p$ .



**Fig. 3.** The left part of the figure compares experimental (● and ○) and theoretical (—) plasmons dispersions of sample A and B. The modes for the the modulated wires are labelled with two indices n/m the first of which corresponds to the lateral confinement perpendicular to the wire axis, and the second is connected to umklapp processes due to the longitudinal modulation. For each sample A or B, one has added theoretical dispersions of classical wires, the widths of which, corresponds to the large (---) and the constricted (·····) part of the modulated wire. The right part shows calculated potential fluctuations associated with mode 0/0 and 1/0 at zone edge for samples A and B.

### 3. Model and interpretation

The fluctuation  $\phi_1(x, y, z)$  of the electrostatic potential associated with the electron density fluctuation at frequency  $\omega$  must satisfy the following equation [3]:

$$\omega^2 \phi_1(x, y, 0) = -\frac{e^2}{\epsilon m^*} \iint \frac{\nabla \cdot (n_0(x', y') \nabla \phi_1(x', y', 0))}{\sqrt{(x-x')^2 + (y-y')^2}} dx' dy' \quad (1)$$

where  $n_0(x, y)$  is the equilibrium density distribution taken as a constant within the wires and vanishing outside. The electrons are assumed to be perfectly confined in the  $z = 0$  plane. We have used a finite differences technique to determine the plasmon dispersion in periodically modulated wires and projected the integro-differential eqn (1) over a basis of local functions constant on each rectangle  $ij$  of a grid covering the unit cell. The diagonalization of the resulting matrix gives plasmon frequencies. The resulting discrete set of linear equations writes:

$$\omega^2 \phi_{1ij} = -\frac{e^2 n_0}{\epsilon m^*} \sum_{k,l} C(q, i-k, j-l) \left[ \frac{2\phi_{1kl} - \phi_{1k+l} - \phi_{1k-l}}{\delta_x^2} + \frac{2\phi_{1kl} - \phi_{1kl+1} - \phi_{1kl-1}}{\delta_y^2} \right] \quad (2)$$

where  $\delta_x$  and  $\delta_y$  are the lateral sizes of the unit rectangle and:

$$C(q, k, l) = \sum_n e^{iqnp} \iint_{\square_{ij}} \frac{dx dy}{\sqrt{(x-k\delta_x)^2 + (y-l\delta_y - np)^2}} \quad (3)$$

where the integral can be analytically determined.

We have obtained an excellent fit of the dispersion curves (Fig. 3), using model parameters (see table in Fig. 1) close to the nominal ones. The gap opening at zone edge strongly increases when the modulation is

deepened (see Fig. 3) and its position follows the  $q = \pi/p$  formula as shown on the polarized Raman spectra obtained on sample A and C (Fig. 2).

The electrostatic potential associated to mode 0/0 (shown in Fig. 3) is fully delocalized within the whole unit cell. We attribute this property to the overlap between the energy bands of mode  $n = 0$  in the unmodulated wires with lateral widths  $l$  and  $w$  respectively (shown in Fig. 3). On the contrary mode 1/0 is confined in the widest part of the unit cell. The energy branch of the odd plasmon  $n = 1$  is indeed lower in the wide constituting wire than in the narrow one: an energy range appears where no allowed modes are available in the narrow section. Mode 1/0 exhibits this behavior in the two samples considered. The corresponding dispersions are very flat.

Moreover, the energy of the confined mode 1/0 decreases when the width of the constriction is reduced though this reduction induces an increasing confinement as can be seen in Fig. 3 and is even smaller than the one of mode 1 (energy shift) in the wire without constriction. This behavior is indeed in contradiction with the usual trend for excitations with increasing dispersion curves, that a stronger confinement induces increasing energy. We have understood that this behavior results from the associated reduction of the average number of 'neighbors' interacting with any site inside the wide part. This implies a significant decrease of the total Coulomb force on the site and thereby, of the plasmon energies. This effect overcompensates the increase due to the confinement.

#### 4. Conclusion

In conclusion, we have reported a quantitative determination of plasmons in doped wires, the width of which is periodically modulated. The results presented here demonstrate the coexistence of longitudinally confined and extended plasmons in 1D systems with modulated boundary conditions. Within a classical frame, we have reproduced the experimental dispersions, including gap openings at zone-edge, deduced from Raman scattering on deep-etched wires. The excellent ability of our theoretical approach, assuming a constant equilibrium density over the whole wire, to reproduce the dispersion of electronic excitations in unmodulated [1] and strongly modulated wires suggests that nearly abrupt boundary conditions apply to oxidized GaAs lateral surfaces, at least at low temperature under illumination. The latter and the observation of large gaps in one-dimensional plasmon dispersion show that our deep RIE process is a suitable method to define complex geometries at a very low scale (100 Å) while preserving the high quality of the initial 2D electron gas. This offers a powerful tool to investigate new physical problems in low dimensional systems with almost arbitrary geometries, for instance the continuous transition from quantum wires to quantum boxes.

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