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$In_{0.75}Ga_{0.25}As$ on GaAs submicron rings and their application for coherent nanoelectronic devices

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Abstract

Electron-phase modulation in magnetic and electric fields will be presented in $In_{0.75}Ga_{0.25}As$ Aharonov–Bohm (AB) rings. The zero Schottky barrier of this material made it possible to nanofabricate devices with radii down to below 200 nm without carrier depletion. We shall present a fabrication scheme based on wet and dry etching that yielded excellent reproducibility, very high contrast of the oscillations and good electrical gating. The operation of these structures is compatible with closed-cycle refrigeration and suggests that this process can yield coherent electronic circuits that do not require cryogenic liquids. The InGaAs/AlInAs heterostructure was grown by MBE on a GaAs substrate [F. Capotondi, G. Biasiol, D. Ercolani, V. Grillo, E. Carlino, F. Romanato, L. Sorba, Thin Solid Films 484 (2005) 400], and in light of the large effective *g*-factor and the absence of the Schottky barrier is a material system of interest for the investigation of spin-related effects [W. Desrat, F. Giazotto, V. Pellegrini, F. Beltram, F. Capotondi, G. Biasiol, L. Sorba, D.K. Maude, Phys. Rev. B 69 (2004) 245324; W. Desrat, F. Giazotto, V. Pellegrini, M. Governale, F. Beltram, F. Capotondi, G. Biasiol, L. Sorba, Phys. Rev. B 71 (2005) 153314; J. Nitta, T. Akazaki, H. Takayanagi, T. Enoki, Phys. Rev. Lett. 78 (1997) 1335] and the realization of hybrid superconductor/semiconductor devices [Th. Schäpers, A. Kaluza, K. Neurohr, J. Malindretos, G. Crecelius, A. van der Hart, H. Hardtdegen, H. Lüth, Appl. Phys. Lett. 71 (1997) 3575].

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1. Introduction

In the framework of conventional electronics, the requirement of an increasing number of devices per unit area has been the leading motivation for progressive device shrinking. As far as coherent electronics is concerned device shrinking is desirable in order to enhance performance and to rise the maximum working temperature. Established technologies for defining nanostructures in two-dimensional electron gases (2DEGs) are: nano gates [2–5], atomic force microscopy lithography (AFML) [6] and etched side-walls. The first two techniques where successfully employed in GaAs/AlGaAs-based nanostructures [7]. Etched nanostructures, despite the strong confinement, have charge depletion layers at the border, the extension of which depends on the type of semiconductor. In the case of GaAs-based 2DEG depletion severely limits the smallest size of a device, being in this case larger than those obtainable using AFML. We want to demonstrate that the use of InGaAs-based 2DEGs overcome this limit allowing to pattern nanostructures defined by etched side walls down to 80 nm line-width providing at the same time a good electric gating.

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2. Device description and fabrication process

The heterostructure employed in this work was grown by MBE on a GaAs (100)-oriented substrate [1]. A sequence of $In_xAl_{1-x}As$ layers of increasing In content was first deposited in order to ensure lattice matching with the upstanding 10 nm layer of $In_{0.75}Ga_{0.25}As$ forming the quantum well. A 10 nm-thick $In_{0.75}Al_{0.25}As$ spacer separates the well from a Si-doping layer ($N_{Si} = 1.3 \times 10^{12}\,cm^{-2}$) placed above. At 4.2 K the electron mobility is $1.1 \times 10^5\,cm^2\,V^{-1}\,s^{-1}$, and the carrier density $9.4 \times 10^{11}\,cm^{-2}$, as estimated from Shubnikov–de Haas measurements on a 60 μm-wide Hall bar patterned on the same heterostructure of the devices presented here. From the mobility and density we deduced the momentum relaxation length $l_m = 1.76\,\mu m$. The ballistic thermal length is $l_T = \hbar v_F/\pi k_B T = 0.46\,\mu m$ at 4.2 K, where v_F is the Fermi velocity and T is the temperature. The first fabrication step consisted in the deposition and annealing of Ni/AuGe/Ni/Au contacts. A Ti mask was then defined on the substrate surface by electron beam lithography, thermal evaporation of Ti, and lift-off. A reactive ion etching process was performed to transfer the geometry of the Ti mask on the semiconductor. The gas mixture employed for the dry etching was $Ar/CH_4/H_2$. The Ti mask was finally removed by wet chemical etching. Tens of devices were fabricated on the same sample showing highly reproducible structural and transport properties. This was extremely useful towards the optimization of devices shape, and, in principle, could be used for tuning circuits parameters.

3. Coherent transport in $In_{0.75}Ga_{0.25}As$-based nanostructures

Two-probe differential conductance measurements were performed with standard lock-in technique at 17.4 Hz. While measuring at 4.2 K or higher temperatures, the bias amplitude was kept at 100 μV, while at 250 mK we used 20 μV. Fig. 1 shows the results for a 350 nm average radius ring. The conductance G exhibits AB modulations at 250 mK with a contrast $\Delta G/G = 20\%$, a remarkably high value for a structure defined using dry etching. This fact joined with the visibility of higher harmonics in $G(H)$'s Fast Fourier Transform (FFT) (see Fig. 1(c)), indicates that our process has a small impact on the structural and transport properties of the patterned nanostructures. The sample electric stability at 250 mK was tested on a time scale of the order of 15 h. The two-probe conductance $G(B)$ is expected to be symmetric with respect to the magnetic field. The high symmetry observed in magnetic field further confirms a good stability of the device. From the frequency value of the first harmonic peak we deduced an effective radius consistent with the lithographically defined average radius. All the rings tested confirmed the same behavior.

The strong and sharp lateral confinement provided by the etched side-walls and the reduced arms line-width lead to a large separation between energy sub-bands. This, joined with reduced electronic paths, allowed us to prove coherent transport in a 200 nm-radius ring similar to that of Fig. 2(c) up to $T = 10\,K$.

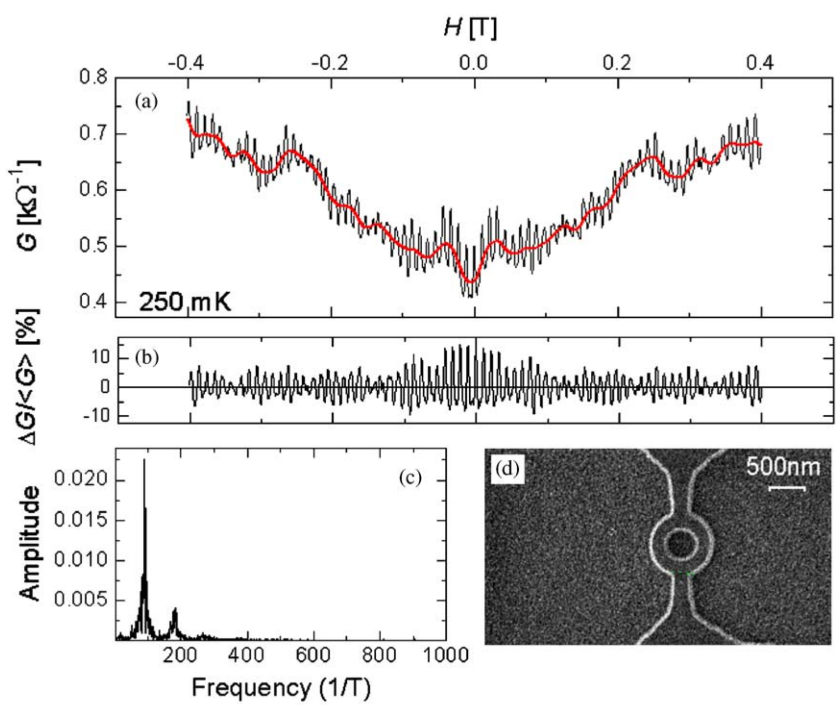

Fig. 1. (a) AB magnetic field conductance oscillation for a 350-nm-mean-radius ring shown in panel (d). (b) $G(H)$ curve of panel (a) where the slowly varying part (thick line) was subtracted. The peak to peak conductance oscillation amplitude is around the 20% of the average conductance value.