Commensurability effects in lateral surface-doped superlattices

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(Received 6 December 2000; accepted for publication 15 February 2001)

We fabricate density-modulated two-dimensional electron systems by shallow compensation doping the donor layer of a modulation-doped heterostructure. Zinc acceptor atoms are diffused from the sample surface which is heated by a focused laser beam. Low-temperature magnetotransport experiments provide evidence that high-quality lateral surface superlattices can be fabricated. In weak periodic one-dimensional potentials, commensurability oscillations are recovered, whereas in strong periodic two-dimensional potentials the semiclassically expected antidot resistance resonances are found to dominate the low-field transport. Additionally, the homogeneity of the laser-induced doping is confirmed by magnetic focusing experiments. © 2001 American Institute of Physics. [DOI: 10.1063/1.1362283]

Semiconductor superlattices have long been a fascinating system to study the influence of an artificial potential modulation on an electronic system. In lateral surface superlattices (LSSLs), a two-dimensional electron system (2DES), for example, a modulation-doped GaAs/Al$_x$Ga$_{1-x}$As heterostructure, is patterned in order to achieve an electron density modulation. Known methods employ holographic illumination, lithographically defined metallic top gates, shallow etching, laser interference melting, atomic force microscope surface oxidation, and growth on vicinal and patterned surfaces. Striking commensurability effects between the electron cyclotron radius and the period length of the superlattice were uncovered in these LSSLs with one-dimensional (1D) and two-dimensional (2D) modulation in low-field magnetotransport experiments.

In this letter, we fabricate lateral surface-doped superlattices (LSDLs) by local and shallow compensation doping the silicon donor layer of a GaAs/Al$_x$Ga$_{1-x}$As heterostructure. The versatility of this method is demonstrated by three different examples of commensurability effects in two-dimensional electron systems. First, in weak 1D LSSLs the known Weiss oscillations with their typical weak temperature dependence at low magnetic fields are recovered, whereas in strong periodic two-dimensional potentials the semiclassically expected antidot resistance resonances are found to dominate the low-field transport. Additionally, the homogeneity of the laser-induced doping is confirmed by magnetic focusing experiments.

In a first set of experiments we have successfully fabricated LSDLs with 1D modulation and periods between $d = 500$ nm and $d = 200$ nm by laser writing an array of 10-μm-long lines across a small Hall bar. The same laser power as used for the calculation shown in Fig. 1(a) was chosen. Measurement results of a sample with $d = 300$ nm are shown in Fig. 2 for two different temperatures $T = 4.2$ K and $T = 1.5$ K. At magnetic fields below $B = 1$ T Weiss oscillations with their typical weak temperature dependence...
FIG. 1. Top: scaled laser-beam profile (dashed) and doping concentration (solid); middle: calculated electron concentration gray scale encoded (black: $3.57 \times 10^{13}$ cm$^{-3}$, white: $0 \times 10^{13}$ cm$^{-3}$); bottom: integrated 2D charge density $n_s$ (circles) and Gaussian fit (solid line). (a) Small laser power, $p_0 = 8 \times 10^{10}$ cm$^{-2}$; (b) large laser power, $p_0 = 1.2 \times 10^{13}$ cm$^{-2}$. Depending on the laser power, small and large potential modulations can be fabricated, while the width of the electron depletion zone remains almost constant, and much below the laser spot size.

FIG. 2. Commensurability oscillations in the 1D LSDSL with period $B = 0.6$ T. Clear resistance maxima are found at magnetic-field strengths corresponding to electron cyclotron orbits around one and four antidots with $d = 500$ nm, as indicated by arrows in Fig. 3, in agreement with a simple electron pinball model. The small dips $\alpha$ and $\beta$ in the Shubnikov–de Haas maxima at smaller filling factors were reproducible in different cooldowns and different samples. Their position forbids the trivial explanation by spin splitting, for example, the dip denoted by $\beta$ lies between filling factors 3 and 4. They may be signatures of the band structure induced by the lateral antidot lattice.

In addition to the first set of experiments, where the presence of Weiss oscillations indicated highly homogeneous laser written lines in the weak potential modulation regime, a third set of experiments was set up to determine the quality of laser-written lines in the strong potential modulation regime. For that reason, we have performed magnetic focusing experiments in a $10 \mu m \times 10 \mu m$ square of electrically isolating laser-written lines with small openings at the corners, as shown in Fig. 4. Clear magnetoresistance oscillations periodic in $B$ are caused by electrons that are specularly reflected at the boundary up to five times. We have experimentally confirmed the expected length dependence of the resonances in a structure with a sidewall.
length of 5 μm, where resonances appeared at double the magnetic-field strengths. The result of this experiment further demonstrates the smoothness of the laser-generated potential modulation.

In summary, we have fabricated lateral surface doped superlattices by selectively $p$-type doping an initially $n$-type GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructure with down to sublaser-wavelength periods. Lateral regularity and homogeneity of the laser-written structures were confirmed by magnetotransport measurements on 1D and 2D LSDSLs. In the former case, Weiss oscillations were observed, whereas in the latter case typical antidot resonances appeared. The high quality of the laser-written lines was further demonstrated by magnetic focusing experiments, showing specular reflection of electrons of up to five times. In contrast to other patterning methods, with our method of compensation doping almost arbitrary lateral potential landscapes may be fabricated. This is simply achieved by adjusting the laser power during the patterning process. LSDSLs with complex unit cells not only in lateral shape but also in electron density should be feasible.

The authors gratefully acknowledge valuable help by M. Huber and the support by the Deutsche Forschungsgemeinschaft via SFB 348.