Parallel quantum-point-contacts as high-frequency-mixers

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The results of high-frequency mixing experiments performed upon parallel quantum point contacts defined in the two-dimensional electron gas of an $Al_xGa_{1-x}As/GaAs$ heterostructure are presented. The parallel geometry, fabricated using a novel double-resist technology, enables the point-contact device to be impedance matched over a wide frequency range and, in addition, increases the power levels of the mixing signal while simultaneously reducing the parasitic source-drain capacitance. Here, we consider two parallel quantum point-contact devices with 155 and 110 point contacts, respectively; both devices operated successfully at liquid helium and liquid nitrogen temperatures with a minimal conversion loss of 13 dB.
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Since the discovery of the quantized conductance in ballistic quantum point contacts (QPCs)[1,2] these devices have been the subject of a large number of theoretical and experimental investigations. Recently, a number of papers have focused upon the high-frequency (HF) device aspects of such devices. For example, the suggestion that photon-assisted tunneling (PAT) may be observed in QPCs[3,4] has led to a number of experimental investigations[5,6] although conclusive proof of this phenomenon in a single QPC remains elusive. In this letter we concentrate on the microwave mixing properties of an integrated parallel QPC device in the ballistic regime and demonstrate that it operates as a sensitive and efficient mixer.

At low temperatures the elastic mean free path in a high-mobility two dimensional electron gas (2DEG) can be as large as 10 μm and the electronic transport through a mesoscopic device such as a QPC therefore ballistic. Consequently, the associated transit time through the active region of the device can be of the order of 1 ps. It has therefore been suggested[7] that the high-frequency operating limit of such devices could be as high as 10 THz. Furthermore, it has been predicted[8] that a QPC should exhibit pronounced nonlinearities at small source-drain bias due to the saturation of the current carrying states within the QPC. Experimentally the observed nonlinearity is less pronounced due both to the self-consistent modification of the subband occupancy[9] as well as to the thermal broadening at the Fermi energy. Nevertheless, we have previously demonstrated[10] at frequencies up to 10 GHz that a single QPC can be operated successfully as a sensitive high-frequency mixer.

The main problem associated with using QPCs as HF-mixing devices lies in the magnitude of the device impedance at the operating point. Typically these devices operate best when only a few one-dimensional subbands are occupied and consequently the real part of the impedance is of the order of several kΩ. For the single QPC device previously investigated[10] the impedance matching of the device to the external 50 Ω experimental setup was achieved using an impedance transformation with discrete, lithographically defined components. The disadvantage of this method of impedance matching lies in its narrow bandwidth which, in the above experiment, limited the device performance. An alternative approach to the impedance matching of the device is to be found in the parallel integration of a finite number of QPCs. The resistive component of the device impedance clearly scales inversely with the number of QPCs and broadband matching over a wide range of operating conditions is readily obtained. This solution offers the additional advantage of increased power levels in the mixing signals and also the automatic reduction of the parasitic source-drain capacitance. For the parallel structures considered in this letter we compare the performance of two devices with 155 and 110 parallel QPCs.

For the fabrication of a parallel QPC device, the conventional lateral geometry, based upon the split-gate technique,[11] is not suitable. Instead we have designed a single gate structure as illustrated schematically in Fig. 1 where the distance of the Schottky gate from the semiconductor surface is periodically modulated by thin, insulating strips of negative resist. Under the influence of a negative gate bias this distance modulation translates into an effective electrostatic modulation along the length of the gate, and hence to the

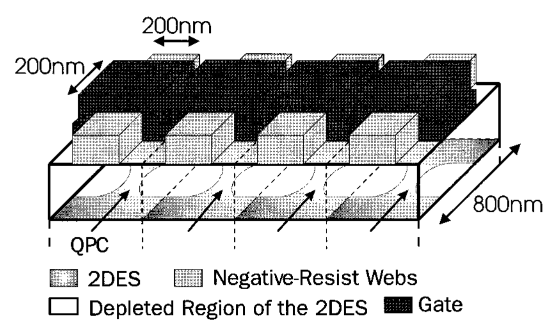

FIG. 1. The parallel device geometry used in these experiments is schematically illustrated. The Schottky gate height is periodically modulated via the insulating resist strips defined on the surface of the semiconductor using high-resolution electron-beam lithography.

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formation of parallel QPCs with a lithographic width and length of 200 nm. In the heterostructure material used for these experiments the 2DEG is situated at a depth of 46 nm; low-temperature transport measurements for this material yield an elastic scattering time and length of 6.1 ps and 1.6 μm, respectively. It is found that an applied bias of -200 mV is sufficient to define the parallel QPCs and that their width, and hence resistance, can be continuously tuned to pinch-off which occurs at ~ 720 mV. Prior experiments on bulk gate devices have shown that the negative resist material used acts efficiently as an insulator and that depletion of the 2DEG occurs first for applied biases beyond -2 V; hence we conclude that the depletion of the conducting channel within the individual QPCs occurs primarily via lateral depletion, and that the transport through the QPCs is ballistic.

The mesoscopic sample was included in an optimized microstrip geometry with impedance matched regions for the source and drain contacts, which permitted the simultaneous measurement of two parallel QPC devices. The gate coupling was achieved via an air-bridge technique[12] designed to isolate the Schottky electrode from the HF signal. The completed sample was then mounted in an external microstrip setup connected to semi-rigid coaxial cables and inserted into the bath of a low-temperature cryostat. The impedance matching of the experimental setup was investigated using voltage standing wave ratio measurements as a function of both the microwave frequency as well as the voltage applied to the gate electrode. Both parallel QPC devices showed the same qualitative and quantitative behaviour; the impedance increased with the applied gate bias from values close to 50 Ω at definition to roughly 150 Ω at pinch-off. Furthermore a systematic increase in impedance with frequency was observed which we attribute to the parasitic, nonresistive elements of our setup. We conclude that we have achieved reasonable impedance matching over the range of operating conditions relevant for these devices.

The quantitative evaluation of the performance of both devices was achieved while operating the QPCs as reflection mixers in the small signal limit. Two HF generators, operating at 2.9 and 2.45 GHz, respectively, were coupled using a power-divider and the HF signal applied to the source contacts via a bias-*T* and directional coupler. The reflected signal was measured at the intermediate frequency 450 MHz using a spectrum analyser. The signal power level was held constant at -35 dB m for all experiments while the power level of the local oscillator was varied from -35 dB m up to -2 dB m. Typical experimental results are shown in Fig. 2 where the power level of the intermediate signal is plotted as a function of the applied source-drain bias for a fixed gate-voltage of -0.5 V. The observed mixing signals have clear maxima at absolute values of source-drain bias around 65 mV. The simultaneously measured current-voltage characteristics are shown in Fig. 3 for typical gate voltages used in the measurements. According to the simple saturation theory[8] the maximum nonlinearity should occur around E_f/e which in our sample corresponds to 10 meV. At small local-oscillator levels we observe a second maximum in the mixing signal at roughly $V_{SD}=10$ mV, however at higher power levels the broad maximum dominates the mixing characteristic. This dominant signal is associated with the self-consistent source-drain characteristics,[9] as is the asymmetry of the observed signal. The optimal conversion loss was determined experimentally by varying the local oscillator power and a minimum value of $C=13$ dB attained at $L_0=-2$ dB m. This value is in reasonable agreement with a small-signal analysis of the simultaneously recorded current-voltage characteristic.

The device performance is summarized in Fig. 4 where the intermediate signal power is plotted as a function of the gate-voltage and source-drain bias for fixed local oscillator and signal power levels of -20 and -35 dB m, respectively. The broad maximum at a gate-voltage of -0.55 V shows that the device is operating best when the individual QPCs are well defined. A naive estimate of the channel

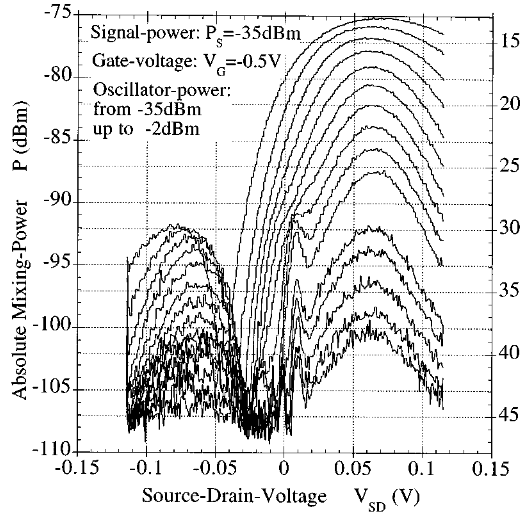

FIG. 2. The intermediate frequency power level is plotted as a function of the applied source-drain bias for different local oscillator power levels (-35 dB m to -2 dB m—corresponding to the lowest and the highest trace) at fixed gate voltage. The signal power level is fixed at -35 dB m, the temperature of the sample is 4.2 K.

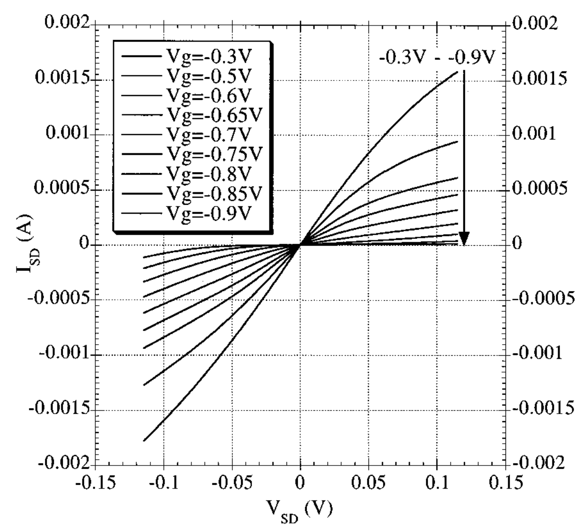

FIG. 3. Current-voltage-characteristics for different gate voltages under microwave bias are shown for the relevant voltage-region from -0.3 up to -0.9 V.

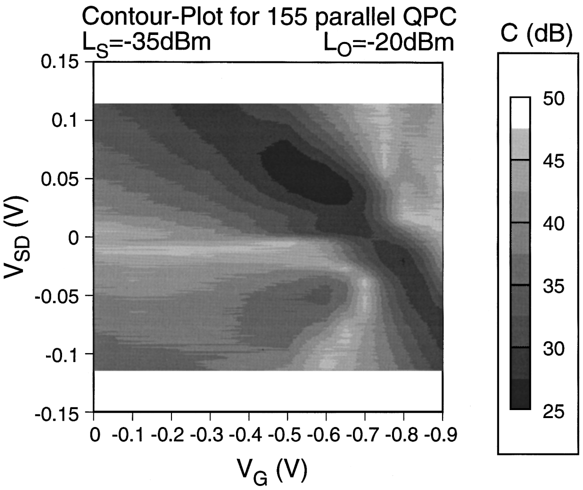

FIG. 4. A summary of the conversion-loss data is shown in a contour plot as a function of the applied source drain and gate voltages. The results shown are for the device with 155 QPCs.

width of each QPC at this gate voltage suggests that roughly one or two subbands are contributing to the current. Beyond pinch-off, which occurs at $V_G = -0.72$ V and is clearly visible in the data, the effectiveness of the device is drastically impaired. This clearly shows that the mixing properties are related to the QPC channels themselves and are not a manifestation of a field effect transistor (FET) structure.

The results for the parallel QPC device with 110 QPCs are both qualitatively and quantitatively very similar; interestingly the intermediate signal level was consistently 2 dB larger than the 155 QPC device. This effect was due to the better impedance matching at the operating point, and more work is required to determine the optimum number of parallel QPCs. As has been previously noted[10] the mixing properties of QPCs result essentially from the width modification of the active channel and are not directly related to the subband structure of the QPC itself. As such, it is to be expected that the parallel QPC devices may be operated at higher temperatures when the subband structure is thermally broadened. This expectation has been confirmed by measurements performed at 77 K upon the two devices; both devices operated successfully with conversion losses only 2 dB larger than at 4 K.

In conclusion, we have fabricated parallel QPC devices using a novel double-resist technique, and have shown that they can be operated as high-frequency mixers with reasonable conversion loss for the configuration considered. It remains to be seen whether these devices could be operated successfully with the HF signal applied to the gate electrode. Ideally, this geometry would better exploit the transistor action of the QPC device, however the impedance matching of the gate presents a significant technological problem.

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