Double 15-nm-wide metal gates 10 nm apart and 70 nm thick on GaAs

Stephen Y. Chou and Paul B. Fischer
Department of Electrical Engineering, University of Minnesota, Minneapolis, Minnesota 55455

(Received 29 May 1990; accepted 3 August 1990)

A method that can fabricate two narrow but thick metal lines separated by a small gap on a bulk semiconductor substrate is described. By opening a 40-nm-wide trench in a single layer of 70-nm-thick polymethylmethacrylate resist on GaAs using high resolution electron beam lithography, and by double shadow evaporations and a lift-off, two 15-nm-wide metal lines 10 nm apart and 70 nm thick were fabricated on a bulk GaAs substrate. The pitch size of the double metal lines is 25 nm. This is a factor of 2 smaller than the previous smallest pitch size on bulk semiconductors. It is found that the width and spacing of the two lines are uniform over tens of microns. It is also found that metals shadow evaporated on top of the resist can be removed successfully by a lift-off, even though they were connected to the metals in the resist trenches. These results suggest that using this method metal lines with even finer linewidth (< 15 nm) can be achieved on a bulk semiconductor substrate.

I. INTRODUCTION

Fabrication of lateral dual-gates electron quantum-interference transistors requires not only that width of gate-metal lines be narrow, but also that separation of the two gates be small and uniform since the separation determines width of a quantum well, and that thickness of the gate-metal lines be large since it determines gate resistance and therefore high frequency performances of the devices.[1,2] Previously, 8-nm-wide metal lines 10 nm apart and 10 nm thick have been fabricated on ultrathin carbon membrane using contamination resists, a high resolution electron beam system, and reactive ion etchings.[3] However, the finest metal lines with the smallest separation on a bulk GaAs substrate are 10 nm wide, 40 nm apart, and 15 nm thick.[4] In this paper, we describe a process which can fabricate double 15-nm-wide metal lines 10 nm apart and 70 nm thick on a bulk GaAs substrate. The method involves high resolution electron beam lithography, a single layer polymethylmethacrylate (PMMA) resist, double shadow evaporations, and a lift-off process.

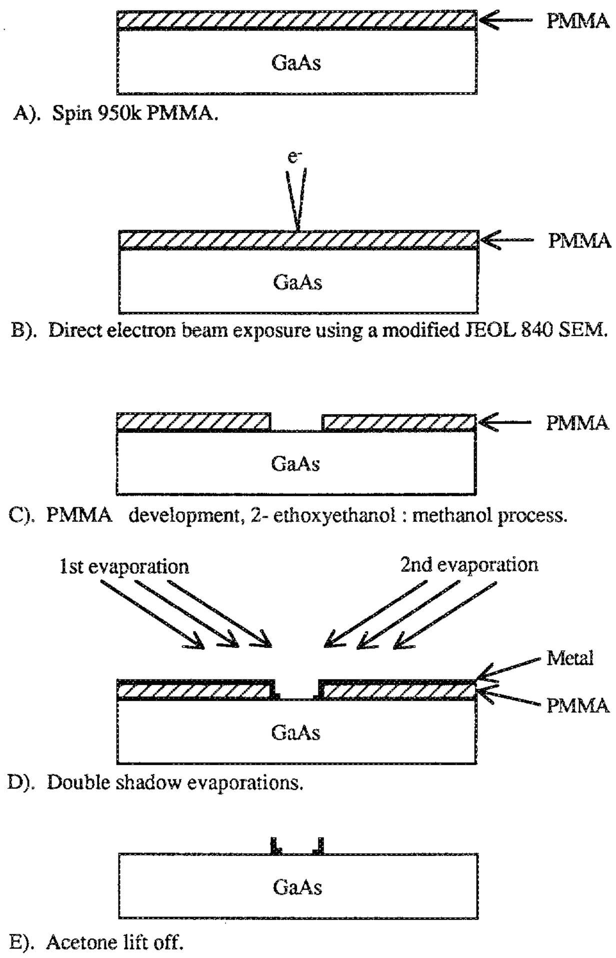
Although the shadow-evaporation technique has been used to fabricate small metal structures on a bulk substrate for many years, it was limited to cases where metals were shadow-evaporated from a fixed angle toward one sidewall of a trench structure.[5-8] Furthermore, a lift-off process was not used in cases where metals were shadow-evaporated on a resist step which has a relatively straight sidewall, since it was believed that metal on the sidewall would be continuously connected to the metal on top of the resist and therefore the lift-off would fail. In the novel process described in this paper, metals were shadow evaporated twice from two nearly opposite angles toward both sidewalls of a resist trench. Moreover, a lift-off process is used to remove the metals on top of the resist, leaving two fine metal lines of a very small spacing on the substrate. Use of lift-off instead of reactive ion etching or ion milling can avoid ion bombardment of semiconductors and therefore preserves high electron mobility of semiconductor materials.

II. EXPERIMENT

Bulk GaAs substrates were spin coated with a single layer 950 000 molecular weight PMMA. While two thickness of PMMA were used, 37.5 and 70 nm, 70-nm-thick resist was used in most of the experiments. After spinning the resist, samples were baked at 160 °C for about 12 h. Line patterns were exposed into resists using a high resolution electron beam lithography system at a beam energy of 35 KeV and at various doses, and were developed in cellosove:methanol (3:1) developer at 22 °C for 7 s. Metals (Ti/Au) were then evaporated onto the resists profiles at angles varying from normal incident to 36° from the normal direction. For some samples metals were shadow evaporated only once from a fixed angle toward one sidewall of resist trench; for other samples metals were shadow evaporated twice from two nearly opposite angles toward both sidewalls of a resist trench. Thus two fine metal lines separated with a narrow gap are formed in the same resist trench. Finally, the metals on top of the resists were lifted off in acetone solvent. The processing sequence for fabricating double metal lines is illustrated schematically in Fig 1.

In the double shadow evaporations as depicted in Fig. 2, linewidth of a metal line on a GaAs substrate from the first shadow evaporation, LW_1, is given by $\mathrm{LW}_1 = W - H \tan\theta_1$, where W is the width of the trench, H is the thickness of the resist, and θ_1 is the angle of incidence from the normal during the shadow evaporation. Width of upper-portion of the metal line is given by $t \sin\theta_1$, where t is the thickness of the metal if it is deposited from the normal. Linewidth from the second shadow evaporation is given by $\mathrm{LW}_2 = W - t \sin\theta_1 - (H + t\cos\theta_1)\tan\theta_2$, where θ_2 is the angle in the second shadow evaporation. Clearly, in order to make linewidths of the two metal lines the same, the incident angle in the second evaporation should be slightly smaller than the first one. The thickness of metal lines fabricated in this way is approximately equal to the thickness of the resist. The important advantage of the double shadow-evaporations process is that the widths and the separation of

0734-211X/90/061919-04$01.00



A). Spin 950k PMMA.

B). Direct electron beam exposure using a modified JEOL 840 SEM.

C). PMMA development, 2- ethoxyethanol : methanol process.

D). Double shadow evaporations.

E). Acetone lift off.

FIG. 1. Basic steps for fabricating double fine metal gates with a small spacing on GaAs substrate.

two metal lines can be smaller than the resolution of resist, and yet thickness of metal lines—therefore the aspect ratio—can be very large, and the width and the separation are very uniform. These features are very desirable for metal gates in lateral dual-gates electron quantum-interference devices.

Our electron beam lithography system consists of a modified scanning electron microscope, JEOL-840A, and a custom beam pattern generator designed and built in house. Several measures have been taken to reduce the noises from floor vibration and electronics. The beam diameter at 35 KV accelerating voltage is about 5 nm. The writing field can vary from $3\times4\ \mu$m to $190\times250\ \mu$m by selecting different magnifications of the microscope. A typical writing field in this experiment is $26\times35\ \mu$m. The pattern generator has 4096×4096 pixels for each writing field.

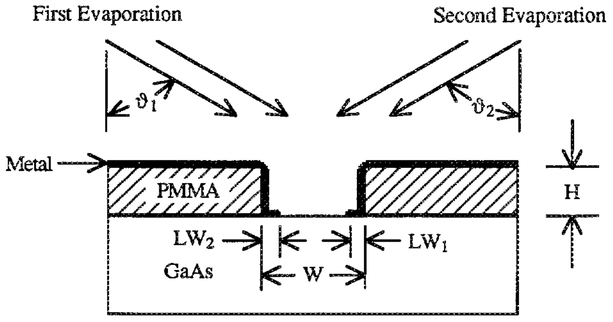


FIG. 2. Schematically illustration of double shadow-evaporations of metals.

III. RESULTS AND DISCUSSION

As the first step, we characterized linewidth of resist profiles written by electron beam lithography at different doses, by evaporating Ti/Au of a thickness of 15/15 nm from normal incidence onto the substrate and lifting off the metals outside of the resist trenches in acetone. Figure 3 shows the linewidths of metal lines after the lift-off versus the beam doses. Some lines were written with double scans in which the electron beam wrote two passes with a separation of 6.2 nm. Due to electron scattering, after the development only one line appeared in the resist. The metal linewidths were examined using a scanning electron microscope which has a maximum magnification of 300 000.

We then examined if the lift-off process would work for metals that were evaporated from an angle toward a resist trench which has rather straight sidewalls. Two identical samples were prepared, both having 70 nm thick PMMA on GaAs substrates. Trenches with widths ranging from 30 to 70 nm were made in the samples by electron beam lithography. The doses for each width were determined from the linewidth versus dose chart given in Fig. 3. One sample was evaporated with metal at a normal incidence and the other was evaporated with metal at the 36° from the normal. Metals on the top of the resist were lifted off in acetone. Examination using a scanning electron microscope showed that for normal evaporation the metal linewidths are consistent with the chart given in Fig. 3. For the 36° angle evaporation, no metal lines were left after lift-off for trenches of width less than 50 nm, while a metal linewidth of 25 nm resulted from

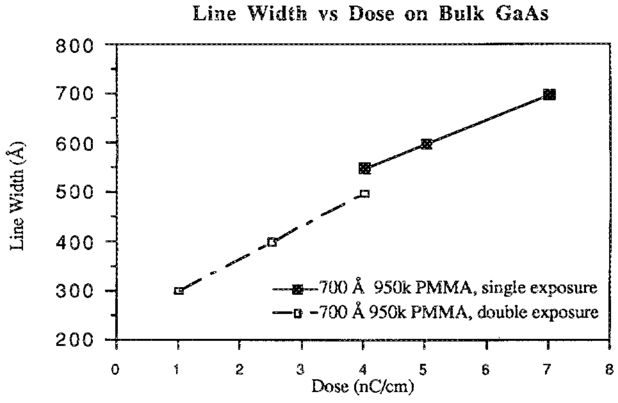


FIG. 3. Width of Ti/Au metal lines after lift-off on GaAs vs line dose of electron beam exposure. The PMMA resist is 70 nm thick, and beam energy is 35 KeV.

the 70 nm wide resist trench. The results from the shadow evaporation is consistent with the calculations using the equations given in Sec. II. Figure 4 shows the metal lines resulting from the normal evaporation and the 36° angle evaporation of metal using a 70 nm wide resist trench. It is quite surprising that lift-off is successful even though the metals in the resist trenches were connected to the metals on top of the resist. Two possible reasons might contribute to this: it would be quite likely the sidewalls of the resist trenches are curved slightly and therefore the metals over the convex corners of the resist profile are thinner and weaker than the other part of the metal film, or metal films deposited using an electron beam evaporator have a weak link at sharp convex corners.

To achieve closely spaced double fine metal lines, metals were shadow-evaporated twice from two nearly opposite angles toward both sidewalls of a resist trench having a width of 40 nm. In the first evaporation, Ti/Au with a thickness 5/5 nm were evaporated at an angle of 28°. And in the second, Ti/Au with a thickness 5/5 nm were evaporated from negative 26°. The slightly smaller angle in the second evaporation takes into account the trench narrowing effect of the first shadow evaporation to achieve almost equally spaced double lines. After lift-off, two 15-nm-wide Ti/Au metal lines of 10 nm apart are left on a GaAs substrate, as shown in Fig. 5. The pitch size of the double metal lines is 25 nm. This is two times smaller than the previous smallest pitch size on bulk semiconductors. Using this shadow-evaporation technique the thickness of the metal should be equal to that of the resist, 70 nm. Examination using scanning electron microscope also showed that the linewidth and line spacing are uniform over tens of microns.

Figure 6 shows two 15-nm-wide Ti/Au metal lines of 40 nm apart and 70 nm thick on GaAs made by double shadow evaporations onto the sidewalls of a 70-nm-wide resist trench. We also successfully applied this double shadow-

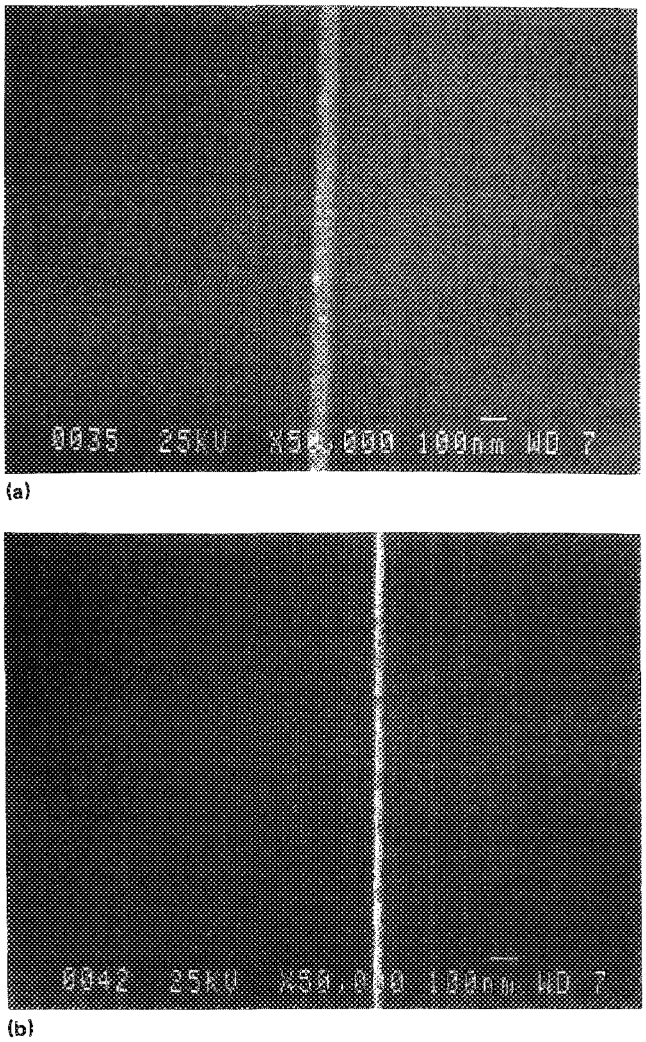


FIG. 4. The Ti/Au lines resulted from evaporateion of Ti/Au from (a) the normal, and (b) 36° angle, into a 70nm-wide PMMA resist trench.

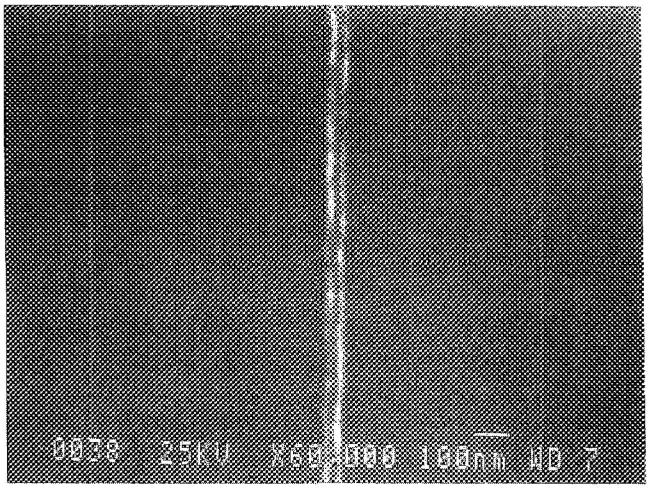


FIG. 5. Double 15-nm-wide Ti/Au metal lines 10 nm apart on GaAs made by double shadow evaporations onto a PMMA resist trenches of width of 40 nm. The evaporation was first from an angle 28° from the normal, and then from a negative 26°. The Ti/Au thickness for each evaporation was 5/5 nm. The PMMA resist was 70 nm thick.

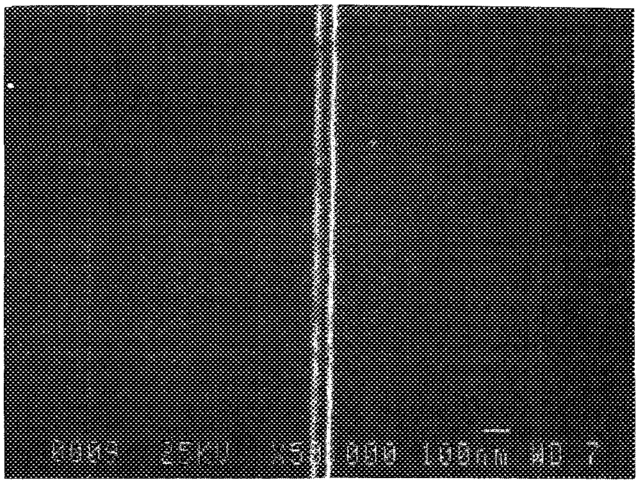


FIG. 6. Double 15-nm-wide Ti/Au metal lines 40 nm apart on GaAs made by shadow evaporation twice. The opening of PMMA trench was 70 nm wide, and the thickness of the resist was 70 nm.

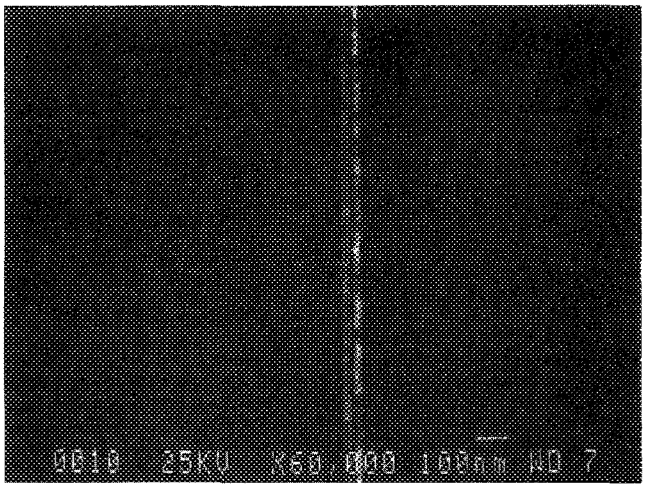


FIG. 7. Double 17.5-nm-wide Ti/Au metal lines 15 nm apart on GaAs made by shadow evaporation twice. The Ti/Au thickness for each evaporation was 10 nm. The opening of PMMA trench was 50 nm wide and the resist was 37.5 nm thick.

evaporation technique to thinner (37.5 nm) PMMA resist. Figure 7 shows double 17.5-nm-wide Ti/Au metal lines 15nm apart on GaAs made by double shadow evaporations. The Ti/Au thickness for each evaporation was 10 nm, and the opening of PMMA trench was 50 nm wide.

Experiments have been repeated several times and results were consistent. To further investigate linewidth, spacing and straightness of the metal lines, cross-section scanning electron microscope (SEM) examination is needed.

IV. CONCLUSIONS

We have described a method that can fabricate two narrow metal lines of a very small gap on a bulk semiconductor substrate. We have demonstrated that by opening a 40-nm-wide trench in a 70-nm-thick single layer of PMMA on GaAs using *e*-beam lithography, and by double shadow evaporations and lift-off, two metal lines of 15 nm wide, 10 nm apart, and 70 nm thick were fabricated on thick GaAs substrate. The pitch size of the double metal lines is 25 nm. This is a factor of 2 smaller than the previous smallest pitch size on bulk semiconductors. We have found that the width and spacing of the two lines fabricated using this method are uniform over tens of microns. We also have found that metals deposited by shadow evaporation can be successfully lifted off. This suggests that using this method, metal lines with even finer linewidth (< 15 nm) can be achieved on bulk semiconductor substrate. We believe this method is useful for fabrication of various lateral dual-gate electron quantum-inteference transistors.

ACKNOWLEDGMENTS

We would like to thank D. R. Allee for providing information about his *e*-beam pattern generator design, and J. A. Boettcher for his contribution in the construction of our e-beam pattern generator. The work is partly supported by Department of Electrical Engineering, Institute of Technology, and the Graduate School at the University of Minnesota, and Army Research Office under Contract No. DAAL03-90-G-0058.

---

[1] S. Y. Chou, J. S. Harris, and R. F. W. Pease, Appl. Phys. Lett. **52**, 1982 (1988).

[2] S. Y. Chou, D. R. Allee, J. S. Harris, Jr., and R. F. W. Pease, Appl. Phys. Lett. **55**, 176 (1989).

[3] A. N. Broers, W. W. Molzen, J. J. Cuome, and N. D. Wittels, Appl. Phys. Lett. **29**, 596 (1976).

[4] H. G. Craighead, R. E. Howard, L. D. Jackel, and P. M. Mankiewich, Appl. Phys. Lett. **42**, 38 (1983).

[5] D. C. Flanders, Appl. Phys. Lett. **36**, 93 (1980).

[6] D. C. Flanders, J. Vac. Sci. Technol. **16**, 1615 (1980).

[7] D. E. Prober, M. D. Feuer, and N. Giordano, Appl. Phys. Lett. **37**, 94 (1980).

[8] E. H. Anderson, C. M. Horwitz, and H. I. Smith, Appl. Phys. Lett. **43**, 874 (1983).