Folded U-Shaped Microwire Technology for Ultra-Compact Three-Dimensional MMIC's

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***Abstract*—A microwire technique has been developed for fabricating three-dimensional (3-D) structures for use in ultra-compact GaAs monolithic microwave/millimeter wave integrated circuits (MMIC). By folding metal into a U-shaped wall and burying it in a relatively thick polyimide insulator, vertical microwires can be made with greatly reduced process complexity. This technique also offers process compatibility with multilevel interconnects. In this paper, the fundamental characteristics of the proposed U-shaped microwire are discussed and its applications to 3-D passive elements and circuits are demonstrated. The characteristics of the U-shaped microwires are almost the same as those of I-shaped microwires and can be accurately estimated and designed by using numerical analysis. The fabricated and designed transmission lines are one-half to one-third the size of conventional lines with the same transmission loss, and if the microwire is also used as a shielding wall, the occupied area can be made much smaller. Miniature inductors made of vertical U-shaped microwires exhibit a self-resonance frequency as high as that of conventional inductors, with one-half the size and offer a great advantage in L- or S-band applications. A fabricated miniature wideband 3-D balun had an insertion loss of 1.5 + 1 dB at frequencies from 10 to 30 GHz, and an amplitude and phase balance of 2 dB and 5°, respectively.**

I. Introduction

The RAPID growth in mobile wireless communication has increased the demand for low-cost and high-performance radio frequency (RF) receivers/transmitters. One promising approach to meet this demand is to combine the necessary functional building blocks of an RF architecture in single-chip monolithic microwave/millimeter wave integrated circuits (MMIC), which results in more compact devices than multi-chip approach. We have developed a microwire technique for use with high-density multifunction GaAs MMIC's. It involves folding metal into a U-shaped wall and burying it in a relatively thick polyimide insulator [1]. The U-shaped microwires that are formed are very useful for reducing the size of GaAs MMIC's. Additionally, the U-shaped vertical microwires are process compatible with multilevel-interconnect structures that use a polyimide insulator [2]–[4], which is another useful approach to making GaAs MMIC's more compact. By combining our proposed technique with the multilevel-interconnect technology, various passive circuits can be formed in an extremely small area.

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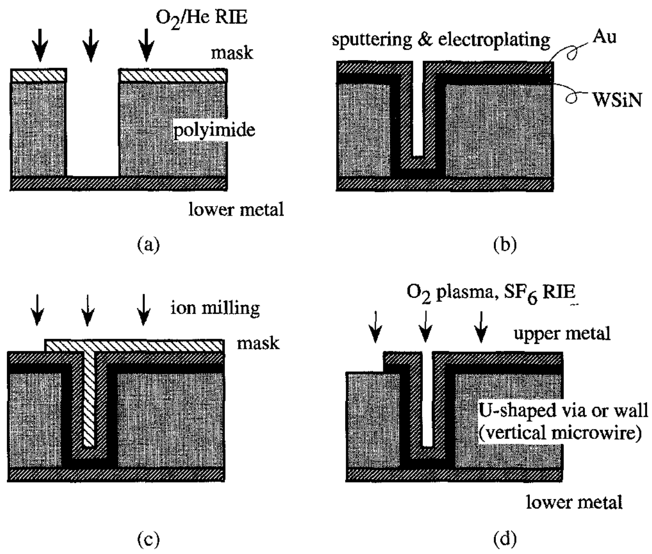


Fig. 1. Process flow to make vertical U-shaped microwires. (a) Deep trench patterns are formed in a 10-μm-thick polyimide insulator layer. (b) A metal sidewall is formed along the surface of the trenches by using low-current Au electroplating. (c) The Au metal is patterned by ion-milling. (d) The sputter deposited WSiN layer is removed by SF6 RIE after ion milling.

In this paper, we explain the fabrication process of the vertical U-shaped microwires and describe their application to passive circuits, i.e., transmission lines, inductors, baluns, couplers, and shielding walls between signal lines.

II. Fabrication Process

To build a completely three-dimensional (3-D) passive circuit structure, fabrication technology with multiple levels of Au interconnects was developed for GaAs MMIC's. A key process is the fabrication of vertical U-shaped microwires, which is similar to micromachining. The main flow of the fabrication process is shown in Fig. 1. First, deep trench patterns are formed in a 10-μm-thick polyimide insulator layer. O_2/He reactive ion etching (RIE) is used to prevent side etching of the polyimide. The ratio of O_2 to He is 2 to 1 and gas pressure is as low as 30 mtorr. The RF power density is 0.2 W/cm^2. The lower metal layer beneath the 10-μm-thick polyimide acts as an etching stopper. The sputtering effect of the He ions effectively eliminates any residue that might be left at the bottom of the deep trench patterns. Second, a 1-μm-thick metal sidewall is formed along the surfaces of the deep trenches by low-current Au electroplating. Prior to the electroplating, WSiN and Au is coated continuously

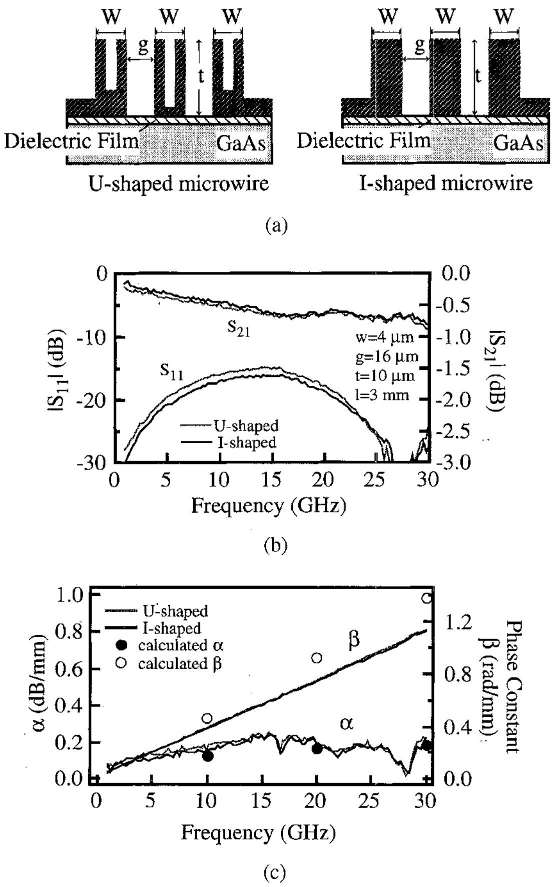


Fig. 2. (a) Cross-sectional view of CPW's made with U-shaped microwires and I-shaped microwires. (b) Measured S_{11} and S_{21} of CPW's with U-shaped and I-shaped microwires. (c) Attenuation constant and phase constant of CPW's as a function of frequency.

by sputtering deposition. Using a current density as low as 0.2 mA/cm^2 for plating results in excellent conformability and uniformity of the plated Au metal. A larger grain size and fewer defects are obtained with lower current density. Third, Au grown on the polyimide surface is patterned by ion milling with a photoresist mask. The sputter deposited WSiN layer beneath Au is very useful as a milling stopper. Finally, the photoresist mask is removed by O_2 RIE and the WSiN milling stopper is removed by SF_6 RIE after ion milling. Sputtered WSiN is also useful for protection of the polyimide during O_2 RIE. This fabrication process was designed with the process simulation tool PARADISE [5].

Combined with WSiN-gate GaAs MESFET technology [6], [7], we usually fabricate six levels of interconnects stacked on a GaAs substrate, where each Au metal layer is 1 μm thick and each polyimide insulator layer is 2.5 μm thick. GaAs MESFET and metal-insulator-metal (MIM) capacitors are formed simultaneously on the GaAs substrate by using the first and second levels of the Au interconnects. In these multilevel-interconnect structures, 10-μm-thick vertical U-shaped microwires, as shown in Fig. 1, can be formed if the second level of the Au interconnect is used as the lower metal and the sixth level is used as the folded U-shaped metal. Therefore, this U-shaped microwire technique, which is process compatible with multilevel interconnects that use isolating polyimide, offers designers a wide range of circuit design options.

TABLE I
SIZE AND TRANSMISSION LOSS IN LINES MADE FROM VERTICAL U-SHAPED MICROWIRES

Coplanar waveguide

	U-shaped	conventional
size	w=4 μm g=11 μm	w=20 μm g=17 μm
loss	0.16 dB/mm	0.15 dB/mm

Thin film microstrip transmission line

	U-shaped	conventional
size	w=4 μm t=10 μm	w= 10 μm t= 4 μm
loss	0.23 dB/mm	0.20 dB/mm

@characteristic impedence 50 Ω
frequency 10 GHz

III. APPLICATIONS

Some examples of 3-D passive elements and circuits that can be devised by using this vertical U-shaped microwire technique are given below.

A. Miniature Transmission Lines and Coupler

Vertical U-shaped microwires can be used as a coplanar waveguide (CPW), as shown in Fig. 2(a). The width, height and gap of the fabricated microwires are 4, 10, and 16μm, respectively, and their metal thickness is 1.3 μm. Although I-shaped microwires have more metal volume, they are less reliable or are not process compatible with multilevel interconnects, because voids form inside the I-shaped microwires if they are fabricated according to the flow in Fig. 1. An experimental CPW was characterized by using an HP8510C network analyzer and on-wafer measurements with microwave probes. The S_{11} and S_{21} parameters were extracted from two-port measurements, and are shown in. Fig. 2(b) as a function of frequency. The performance of the U-shaped microwires was almost equal to that of the I-shaped ones even though the cross-sectional area is one-third less. This is because the electromagnetic field is concentrated at the gap of the CPW, so the internal conductor of the I-shaped microwires contribute little to the transmission characteristics. Fig. 2(c) shows the attenuation constant and the phase constant as a function of frequency. The attenuation constant and the phase constant were extracted by measuring the S_{21} parameters of CPW's with different line lengths. A simulation was also performed using the finite-element method (FEM) [8] in the case of the I-shaped microwires. The measured results show fairly good agreement with the simulated ones. A slight difference in the phase constant between the measured and simulated results appeared because the SiN insulator under the CPW was not taken into consideration in the simulation. The transmission loss was as low as that of a conventional CPW used in a uniplanar MMIC, where the metal thickness of the CPW is 3 μm [9]–[11]. A characteristic impedance of 50 Ω was attained when the gap was as narrow as 11 μm, which shows that the intrinsic area occupied is reduced to one-half the area of a conventional CPW, which has a width of 20 μm and a gap of 17 μm. The size and transmission loss of the CPW with vertical U-shaped microwires are summarized in Table I.

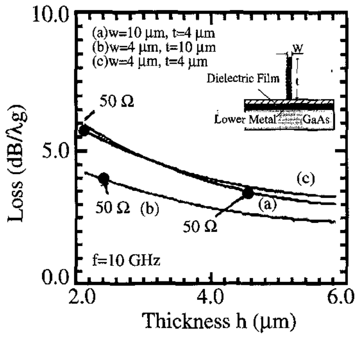
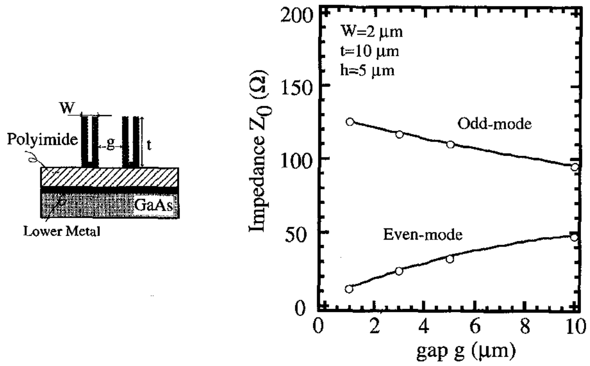


Fig. 3. Simulated transmission loss of TFMS versus polyimide insulator thickness using the finite-element method.



(a) (b)

Fig. 4. Design of a miniature broadside coupler consisting of vertical U-shaped microwires: (a) cross-sectional view of coupled microstrip lines and (b) even- and odd-mode characteristic impedance as a function of the coupled microstrip line gap calculated using the finite element method.

Fig. 3 shows the transmission loss in a thin-film microstrip (TFMS) line versus the polyimide insulator thickness, which was simulated using the FEM. The simulated TFMS structure is shown in the inset of Fig. 3. Curves (a) and (c) represent conventional TFMS lines with, respectively, metal width $W =$ 10 μm and metal thickness $t = 4$ μm, and $W = 4$ μm, and $t = 4$ μm. Curve (b) represents a TFMS line made from I-shaped microwires with $W = 4$ μm and $t = 10$ μm, which probably exhibits almost the same characteristics as a TFMS line made from U-shaped microwires, just as in a CPW. At 50-Ω characteristic impedance, curve (b) shows almost the same transmission loss as curve (a), while curve (c) is 1.5 dB higher. However, for curve (b) and (c), the width of the signal line was only two-fifths of that for curve (a). Therefore, an advantage of the U-shaped microwire technique is that it allows the TFMS width to be minimize as shown in Table I.

A miniature broadside coupler can be designed by using the U-shaped microwires as shown in Fig. 4(a). The coupler is constructed of two U-shaped microwires and effectively provides tight coupling. As the two microstrip lines are entirely symmetric to each other, which is the main feature of this coupler, two orthogonal modes propagate in the structure. If the conventional even- and odd-mode design is applied, even and odd characteristic impedances of 121 Ω and 21 Ω, respectively, are required for a 3-dB coupler with a characteristic impedance of 50 Ω. The propagation constant and the characteristic impedance of each mode were calculated using the FEM. Fig. 4(b) shows the calculated characteristic impedance of each mode. When the width, height, and gap of a microwire on a 5-μm-thick insulator are 2, 10, and 2.5 μm, respectively, and the coupled microstrip lines are buried in a polyimide insulator, the desired even- and odd-mode characteristic impedance is attained. When the designed broadside coupler is fabricated using the U-shaped microwire technique with a meandering configuration, the intrinsic area occupied will be one-fifth to one-tenth the area of a conventional coupler.

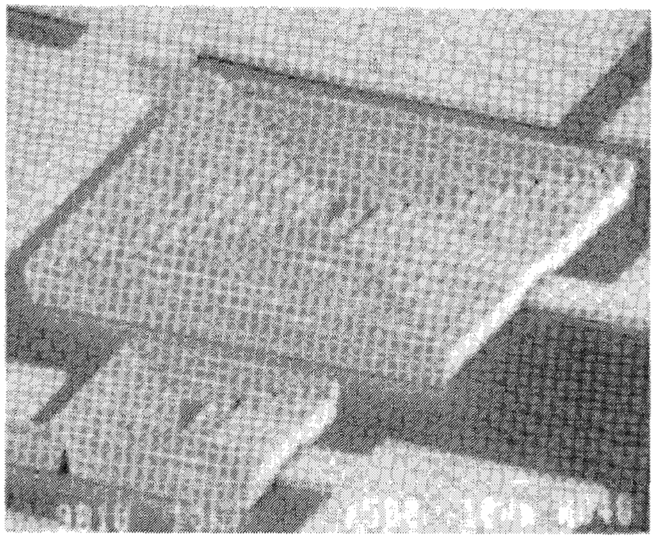


Fig. 5. SEM photograph of fabricated spiral inductors on the chip.

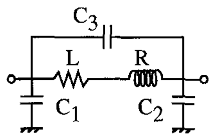


Fig. 6. Lumped element equivalent circuit for the integrated inductor.

B. Miniature Inductors and Filters

The U-shaped microwire technique can also be applied to fabricate miniature inductors. A scanning electron microscopy (SEM) photograph of spiral inductors fabricated with U-shaped microwires is shown in Fig. 5, where the inductors have a 10-μm metal thickness, 4-μm metal width, and 4-μm metal-metal spacing with four and nine turns. A uniplanar MMIC layout, where the ground plane is at the front of the wafer, was used and the underpass of the inductors is at the first-level metal [12]. In this work, the polyimide in the metal-metal spacing and around the inductor was removed by dry etching. The fabricated inductors were characterized through on-wafer measurements. The parasitic capacitance and the contact resistance were accurately subtracted from the measured data by calibration at the open, short, and load sites. The measured inductor data were fitted with the lumped element equivalent circuit (Fig. 6) by using the HP-EEsof linear simulator Touchstone.

Fig. 7(a) shows the occupied area of meandering and spiral inductors made of U-shaped microwires as a function of inductance, where the metal width $W = 4$ μm, the metal-metal spacing $G = 4$ μm, and the metal height $t = 10$ μm. The experimental data for inductors made of conventional microwires are also given in the same figure. The specifications of the conventional microwire (a) is $W = 10$ μm, $G = 4$ μm, $t = 3.5$ μm, which are generally used in uniplanar MMIC technology [11]; the specifications of the conventional microwire (b) are $W = 4$ μm, $G = 4$ μm, $t = 3$ μm, and those of conventional microwire (c) are $W = 10$ μm, $G = 10$ μm, $t = 3$ μm. In these conventional structures, the inductors are composed of two levels of interconnects with via arrays and the underpass of the spiral inductors is at the first-level metal. As Fig. 7(a) shows, the meandering and spiral inductors made with U-shaped microwire are half the size of those made with the conventional microwires (a) and (c), and as small as the inductors made with the conventional microwire (b).

Fig. 7(b) shows the self-resonance frequency and series resistance of meandering inductors as a function of inductance. The experimental S_{11} and S_{21} parameters of the meandering inductors were fitted to the equivalent circuit for a frequency range from 0.5 GHz to 50 GHz. Excellent agreement between measured data and the models was achieved over the entire frequency range. The vertical U-shaped microwire effectively lowers the parasitic resistance due to its greater metal height, and the fitted series resistance is only three-fourths that of the conventional microwire (c). The self-resonance frequency f_{SR} was calculated from the simple equation for the case where the port two is shorted to the ground, that is

$$f_{SR} = \frac{1}{2\pi\sqrt{L(C_1 + C_3)}}. \tag{1}$$

There was a concern that the f_{SR} of the meandering inductor made from this vertical U-shaped microwire would be inferior because of the greater metal height and narrower metal-metal spacing. Although the fringing capacitance C_3 is strongly affected by the metal-metal spacing and the metal height, it is much smaller than, or at most 10% of, C_1 or C_2 which are mainly affected by the insulator under the microwire and the spacing between the inductor and the ground. Therefore f_{SR} is less degraded than with the conventional microwire (c) and the inductance is fairly independent of frequency as a result of the high f_{SR}.

Fig. 7(c) shows the self-resonance frequency and series resistance of spiral inductors as a function of inductance. In this case, the experimental S_{11} and S_{21} parameters were fitted for the frequency range from 0.5 GHz to 2 GHz which will be used for the application of L-band mobile wireless communication products. The series resistance when using the U-shaped microwire is as small as for the conventional microwire (a) and about one-third that of the conventional microwire (b) which is the same size. Spiral inductor made of U-shaped microwire, therefore should have a great advantage in the submicrowave frequency range, i.e., for L-band or S-band application, where compact inductors with high

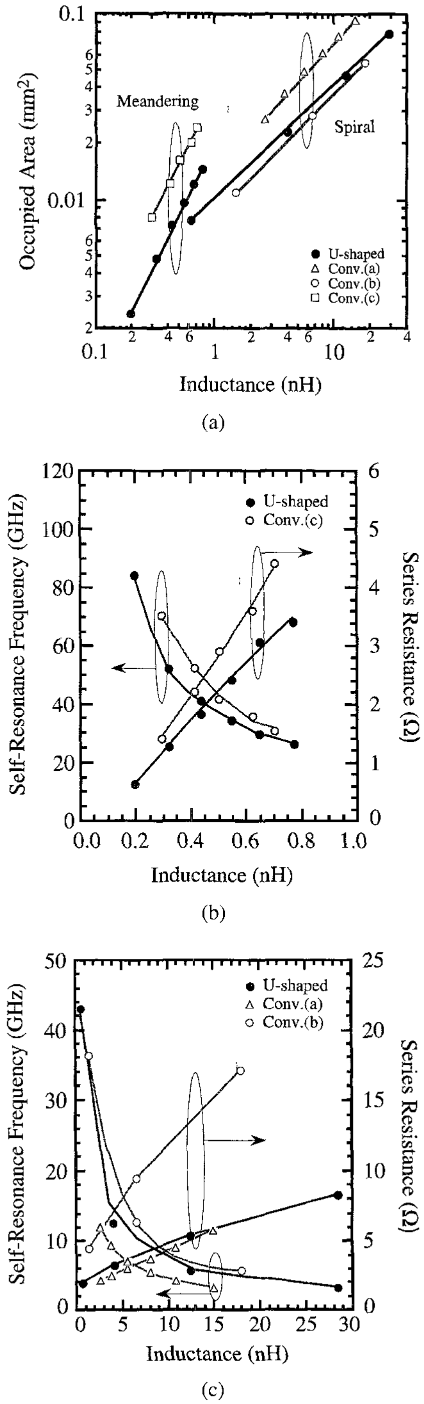


Fig. 7. Measurement and equivalent circuit element data for fabricated inductors: (a) occupied area versus inductance of meandering and spiral inductors, and self-resonance frequency and series resistance of (b) meandering inductors and (c) spiral inductors as a function of inductance.

inductance are especially useful. We also calculated f_{SR} from (1). Because the fringing capacitance is as small as that of the conventional microwires (a) or (b) for the same reason as with the meandering inductors, f_{SR} is almost as large as for the conventional microwires. Moreover, we found the calculated Q-factor from the models was over 30.

In order to verify the Q-factor experimentally, we fabricated a low-pass filter with inductors made of the U-shaped microwires. The circuit configuration is shown in the inner

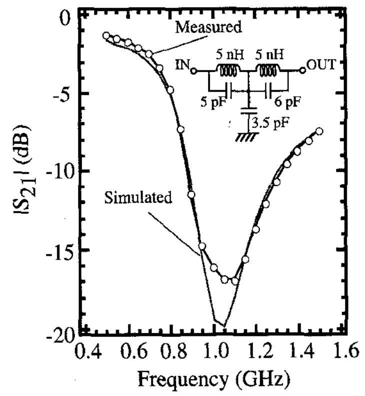


Fig. 8. Measured characteristics of a low-pass filter with MIM capacitors and miniature inductors made with vertical U-shaped microwires. The inner figure is the circuit configuration of the low-pass filter.

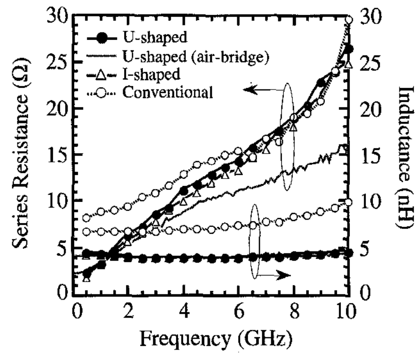


Fig. 9. Series resistance and inductance of spiral inductors as a function of frequency.

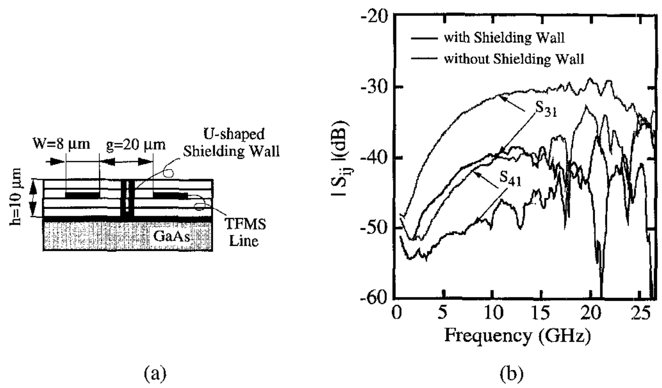


Fig. 10. Shielding effect of U-shaped vertical metal wall in a multi-level-interconnect structure: (a) cross-sectional view of TFMS lines with a shielding wall and (b) isolation in a TFMS line with and without a shielding wall.

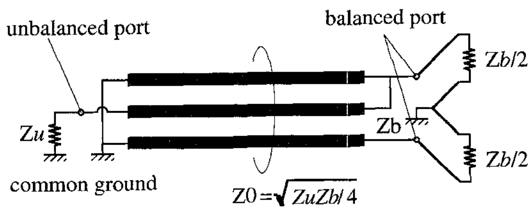
part of Fig. 8. It consists of two 5-nH spiral inductors and three MIM capacitors. The spiral inductor was designed to have a Q-factor of 30. The MIM capacitor was composed of the first and second levels of the interconnects and a 0.2-μm-thick insulating SiO_2 layer was formed by plasma-enhanced chemical vapor deposition (P-CVD). The intrinsic area of the experimental low-pass filter was 780 μm square, which is one-fifth the size of a conventional one. Fig. 8 also shows the measured S_{21} parameter of the fabricated low-pass filter as a function of frequency. The insertion loss was under 3 dB and the attenuation was 15 dB for a 300-MHz offset. The simulated results agreed well with the measured data when the Q-factor of the inductor is assumed to be 5 at 1 GHz, and the Q-factor of the MIM capacitor to be infinity. The Q-factor estimated from the low-pass filer is much lower than that calculated from the equivalent circuit model. This suggests that the parasitic resistance of the spiral inductors was still larger than the dc value and had a strong frequency dependence.

To clarify this phenomenon, the experimental data were fitted over an extremely narrow frequency range. Fig. 9 shows the frequency dependence of the series resistance and inductance obtained from this narrow-range fitting. For comparison, data for inductors made from the conventional microwire (a), I-shaped microwires and U-shaped microwires with an air bridge are also shown. In the case of the U-shaped microwires with an air bridge, the insulating SiN under the microwires was removed by RIE, so that the bottom of the microwire is exposed to air. The inductance of each type was fairly independent of frequency as a result of their relatively high f_{SR}. However, the series resistance of both the U-shaped and I-shaped microwires increased more steeply against frequency than that of the conventional microwire (a). Although the surface area of a U-shaped microwire is larger than that of an I-shaped one, the series resistance is almost the same. This suggests that the skin effect does not contribute to the steep increase in the resistance, probably because the electromagnetic field is mainly concentrated at the bottom of the microwire.

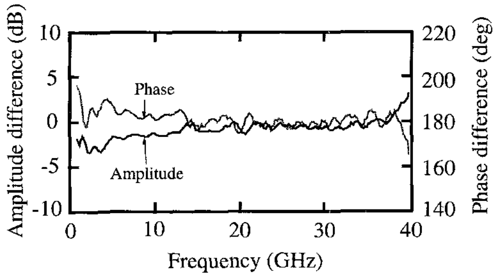
The slope of resistance for the U-shaped microwire with an air bridge is more gentle than that of a conventional microwire (a), which suggests that the concentration of the electromagnetic field is relaxed because the bottom of the microwires is open to air. If the bottom of a microwires is composed of low-permittivity insulator, the series resistance of the U-shaped microwire is less dependent on the frequency. Therefore, the spiral inductor made from the U-shaped microwire has the potential to attain a higher Q-factor when it is made on a lower-permittivity insulator.

C. Shielding Walls

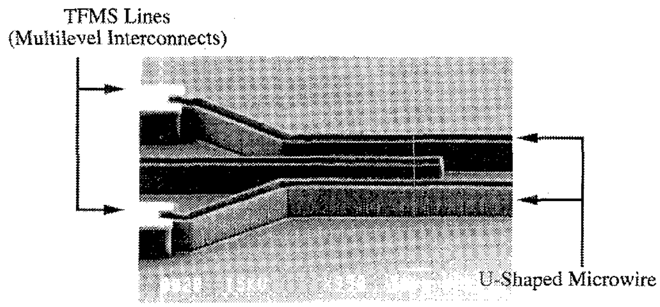
U-shaped microwire technology is also useful for isolation of two signal lines. Fig. 10(a) shows a cross-sectional view of a U-shaped vertical wall being used as shielding between two TFMS lines in a multilevel-interconnect structure [13]. The width of the two TFMS lines is 8 μm and the gap is 20 μm. The polyimide thickness between the TFMS lines and the ground is 5 μm. Fig. 10(b) shows the measured S_{31} and S_{41} parameters as a function of frequency with and without the U-shaped wall. The 10-μm-high U-shaped vertical wall buried in the thick polyimide insulator improved the isolation by about 10 dB. When this U-shaped vertical wall was applied to an CPW, only a small improvement of 2–3 dB was obtained because electromagnetic waves propagate through GaAs substrate. So, in the case of a TFMS line or an inverted microstrip line (IMSL) [14], one of the big advantages of such a wall is that it greatly reduces the area for the strong isolation needed to prevent crossover.



(a)



(b)



(c)

Fig. 11. Miniature wideband 3-D balun made with U-shaped microwires: (a) circuit diagram, (b) amplitude and phase balance as a function of frequency, and (c) SEM photograph of the transition point from U-shaped microwire to TFMS line. The polyimide was removed so that the microwire structure could be seen.

D. Miniature Balun

We also fabricated a miniature wideband 3-D balun [15]. Fig. 11(a) shows the circuit diagram of a GaAs MMIC balun. Three narrow U-shaped microwires with the quarter wavelength, 1.55 mm, at the center frequency of 20 GHz were formed with a width of 6 μm and a height of 10 μm. The conductor gap was 14 μm because the unbalanced and balanced characteristic impedance was designed to be 100 Ω. The insertion loss was 1.5 ± 1 dB at frequencies from 10 to 30 GHz, and the return loss was less than 10 dB at frequencies from 13 to 28 GHz. The amplitude and phase balance was 2 dB and 5°, respectively, at frequencies from 5 to 35 GHz as shown in Fig. 11(b). The intrinsic area was only 450 μm $\times$ 800 μm, which is about one-fifth to one-third the area of recently reported miniaturized MMIC baluns [16]–[17]. Fig. 11(c) is an SEM image of the fabricated U-shaped microwires and the point of transition to TFMS lines.

IV. Conclusion

A novel microwire technique that is process compatible with multilevel interconnects that use a polyimide insulator has been developed. The vertical U-shaped microwire has almost the same characteristics as an I-shaped microwire and can be accurately estimated by using the FEM. Because this 3-D technology can be used to make a wide variety of highly miniaturized and multifunction passive circuits, it enables us to implement ultra-compact GaAs MMIC's. With this technique, circuit designers can take advantage of smaller chip areas and greater design flexibility to produce higher-performance GaAs MMIC's.

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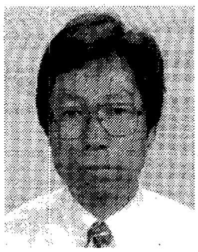

Kiyomitsu Onodera (M'93) was born in Tokyo, Japan, on August 10, 1960. He received the B.S. and the M.S. degrees in instrumentation engineering from Keio University, Tokyo, Japan, in 1984 and 1986, respectively.

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Mr. Onodera is a member of the Japan Society of Applied Physics and the Institute of Electronics, Information and Communication Engineers (IEIEC) of Japan.

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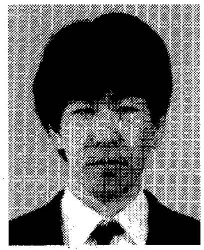
Ichihiko Toyoda (M'91), for a photograph and biography, see this issue, p. 2346.



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Tsuneo Tokumitsu (M'88), for a photograph and biography, see this issue, p. 2346.