Development of Linear Solenoid Driver IC

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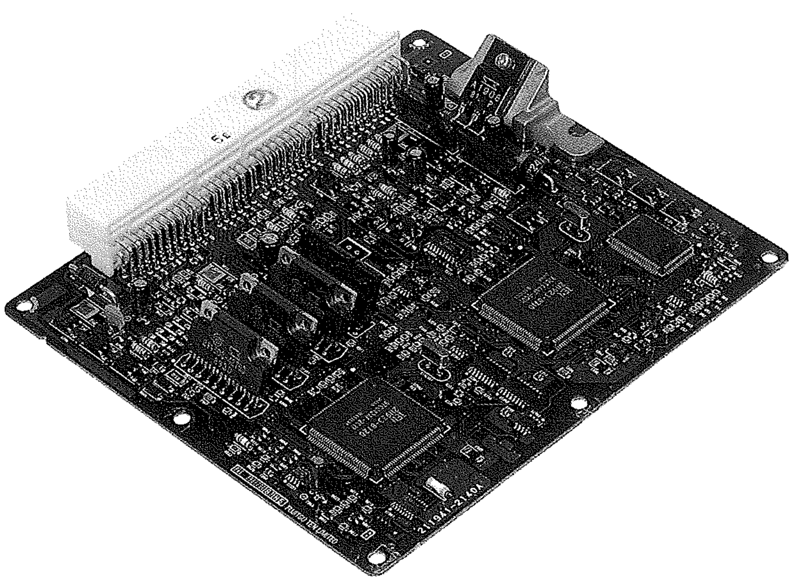

Abstract

Recent demands for cars that is driving safely, low fuel consumption, low emission, and driving comfort have been drawing furnishing of electronic devices for automobile application. We developed a linear solenoid driver IC which can control shock-free automatic transmissions and variable timing valve systems to match such demands.

We have developed the ASIC with BCD process (Bipolar, CMOS, DMOS mixed process)and it cuts down number of components, work board size and cost, and increases the productivity simultaneously.

1. Introduction

In the future, the prevalence of shockless automatic transmissions and variable intake-exhaust valves will likely lead to a sharp increase in the use of linear solenoid control circuits. About three or four linear solenoid control circuits are expected to be mounted on each electronic control unit (ECU). Under such circumstances, we have developed a new linear solenoid driver IC with the aim of boosting productivity and achieve highly advanced functions.

The custom IC currently in use requires two on-ECU adjustments per circuit. This greatly affects tact time during manufacture.

To make on-ECU adjustments unnecessary, this IC is trimmed on the chip. We also adopted the BCD process to realize significant reductions in the number of ECU-mounted parts, mounting area, and system price.

2. Outline of Linear Solenoid

2.1 Linear Solenoid

Figure 1 shows a linear solenoid consisting of a control current connector, a coil, a plunger, and other components. This solenoid can control a hydraulic pressure linearly in accordance with the control current.

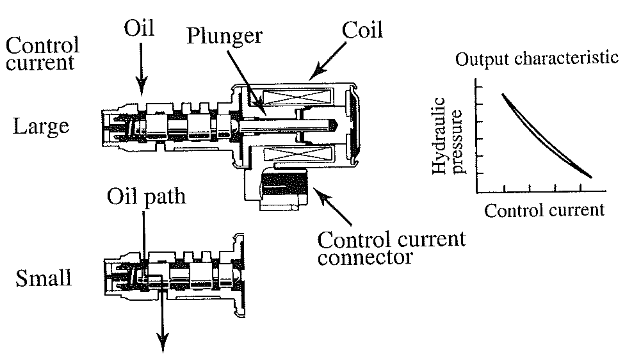

Figure 1 Linear solenoid

2.2 Uses of Linear Solenoid

2.2.1 Uses

Table 1 lists the main uses of linear solenoid.

2.2.2 Example of application to variable intake valve

An example of application to a continuously variable intake valve timing mechanism is explained here.

(1) Outline

To realize high efficiency and torque as if customized to accommodate every rotation area, the linear solenoid should vary the intake valve timing appropriately according to its engine·operating conditions. Under a low load as when driving in a town, the linear solenoid raises the intake-exhaust efficiency to improve the fuel efficiency as well as reduce its exhaust emission. (Figure 2)

Table 1 Uses of solenoid valve

Use	Control section	Effect
Transmission	Planetary gear	- Reducing transmission shocks - Raising fuel efficiency
	Lockup clutch	
	Line pressure	
Intake-exhaust valve timing	Variable intake-exhaust Valve timing	- Low exhaust emissions - Raising torque and output - Raising fuel efficiency

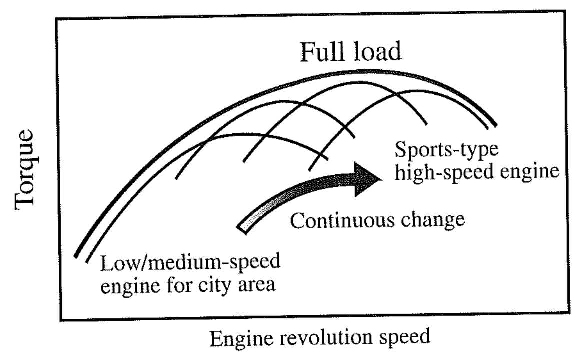

Figure 2 Optimum torque curve

(2) Configuration

The variable valve timing control system in Figure 3 mainly consists of an ECU, a linear solenoid that controls the hydraulic pressure in accordance with ECU instructions, and a VVT pulley that varies the intake valve timing continuously in accordance with the hydraulic pressure.

(3) Operation

The ECU determines the optimum valve timing from the operation status and controls the hydraulic pressure supplied to the VVT pulley with the linear solenoid. With the supplied hydraulic pressure, the VVT pulley moves the movable piston having helical splines (twisted vertical grooves) in the direction of the cam axis. Thus the phase between the intake cam shaft and timing belt pulley is changed so as to vary the intake valve timing continuously. (Figure 3)

As explained above, the optimum valve timing control that depends on the operation status produces the effects listed in Table 1.

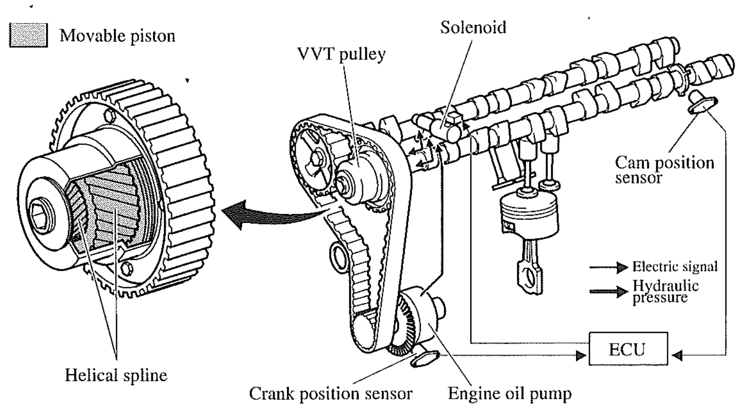

Figure 3 Variable valve timing control system

3. Development

3.1 Targets and Measures

As explained in Chapter 1, three or four linear solenoid drive control circuits are mounted per ECU. From the year 2000, Fujitsu TEN expects to use at least 100,000 pieces monthly. The custom IC currently in use requiring two adjustments per circuit increases the tact time on the production line. With the five items in Table 2 as the targets of development, we started developing a new linear solenoid driver IC (referred to as the new driver IC in this document).

Table 2 Targets and measures

Target	Measures
1) High-resolution output current (0.4mA/LSB)	Adopting high-precision current detecting circuit and 12-bit DA converter
2) No adjustment at ECU	IC trimming on chip
3) High/low side drivers	Building in output power devices and charge pump
4) Multichannel drive	Adopting serial communications
5) Fewer external parts	Adopting the BCD proces

3.2 Specifications of New Driver IC

From Table 2, we determined electrical characteristics and built-in functions.

3.2.1 Electrical functions

(Output current precision)
When 1A is set: 1A±4.5%
(Conditions)
Ambient temperature: -40 to +105 °C
Battery voltage +B: 10 to 16 V
IC supply voltage VCC: 5 V ±1.5%
Solenoid load: 5.3Ω/27.2 mH (typical example)
Current detecting resistor: 0.33Ω (±1%, 150 ppm/°C)

3.2.2 Built-in functions

1) High and low side drive output selection function
2) 16-bit serial input/output communication function (Current setting: 12 bits)
3) Self-diagnostic function (overcurrent, overheat, abnormal control, and communication error)
4) IC protection function (overcurrent protection and overheat protection)

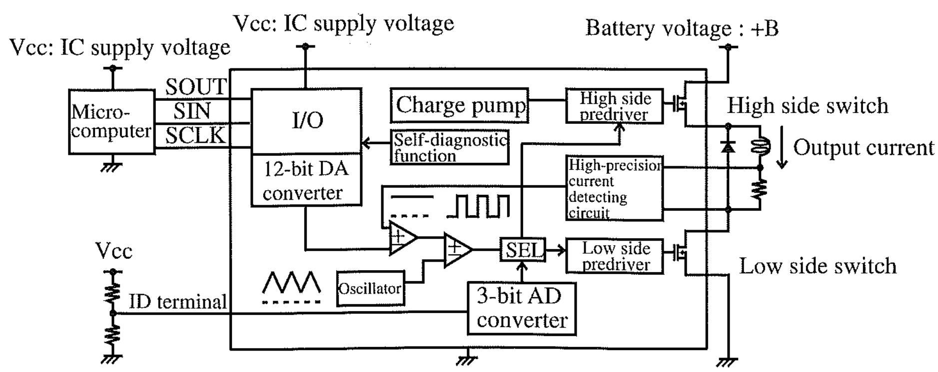

Figure 4 Block diagram of linear solenoid driver

4. Outline of New Driver IC

4.1 Configuration of New Driver IC

Using Figure 4, this section explains the configuration of the new driver IC briefly.

The ECU microcomputer sets the optimum output current of the linear solenoid in accordance with the engine operation status via master-slave serial communications. The 12-bit DA converter then outputs a voltage depending on the set value. Then, this voltage and the feedback voltage (converted from the output current) are amplified differentially. This amplified voltage forms a PWM signal at the comparator with a triangular wave from the oscillator and controls the high or low side switch to regulate the output current.

The high or low side drive is set by applying an external DC voltage through the ID terminal.

4.2 Configuration of High-precision Current Detecting circuit

Using Figure 5, this section goes over an example of low side drive for output current control by applying PWM control to the low side switch. (The high side switch is normally on.)

The output current flowing through the solenoid is as shown in Figure 5. The current detecting resistor detects this current as a voltage depending on the on/off state of the low side switch. The detected voltage becomes a potential close to the GND voltage when the switch is on and close to the battery voltage when it is off.

The problem here is that the common-mode input voltage is generally limited as shown in Figure 6 if the operational amplifier circuit has a PNP or NPN configuration. To control the output voltage to the target characteristic, the current detecting circuit should detect a current throughout the area of the set value.

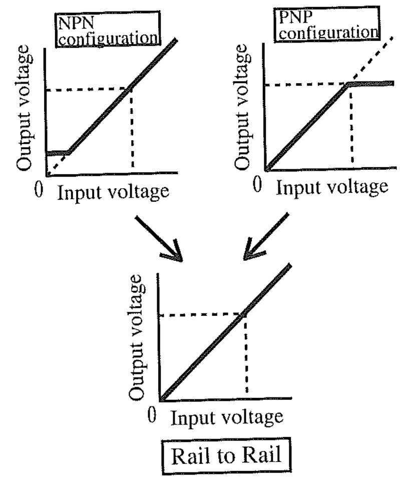

Figure 6 Operation limit of operational amplifier

Therefore, we created the current detecting circuit by combining two types of operational amplifier circuits (Figure 5) for high-precision current detection in a wide input voltage range. This circuit detects a current at AMP1 when the positive and negative sense voltages are smaller than +B/2 and at AMP2 when the positive and negative sense voltages are greater than +B/2.

During high side drive, the current is only detected at AMP1 because the low side switch is normally on and the sense voltage is always lower than +B/2.

4.3 12-bit DA Converter

For the 12-bit DA converter, the master-slave R-2R generally used for 8 to 12 bits was adopted.

4.4 On-chip Trimming

4.4.1 Effectiveness of on-chip trimming

To make on-ECU adjustments unnecessary as explained in Chapter 3, we analyzed the main factors of

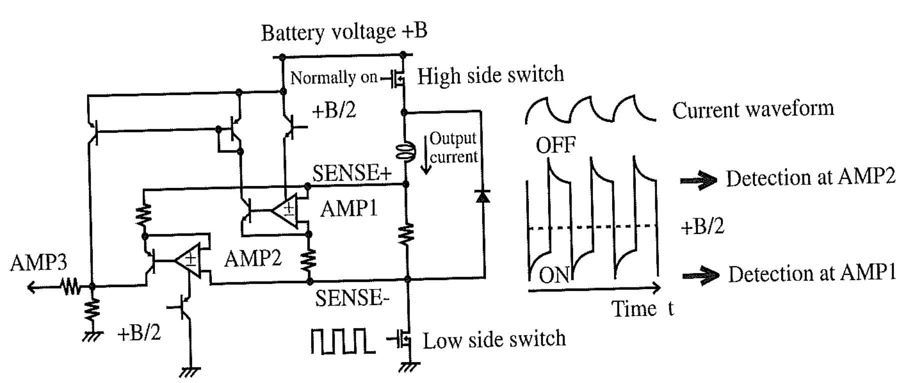

Figure 5 High-precision current detecting circuit

output current fluctuations in the newly adopted linear solenoid drive control system and studied the possibility of eliminating adjustments. The main factors of fluctuations are as follows:

1) Current detecting resistor: ±1.0%
2) Current detecting resistor (temperature characteristic: 150 ppm): ±1.2%
3) Current detecting circuit: ±1.6%
4) Reference voltage precision (IC external power supply: 5 VDC): ±1.5%
5) DA converter output precision: ±0.1%

....

Total (target: ±4.5%): ±5.4%

Considering the above factors, the fluctuations are as follows:

IC external fluctuation: 1) + 2) + 4) = ±3.7% .... 6)
IC internal fluctuation: 3) + 5) = ±1.7% .... 7)

To make on-ECU adjustments unnecessary, we should suppress the IC internal fluctuation 7) within (target - 6)>) ±0.8%. We judged that IC external adjustments will be unnecessary if the chip is trimmed by 2 - 3 bits.

4.4.2 Output current error factors

There are two types of output current error factors for the set value: offset and gain (Figure 7).

The adjustment methods and the measures for achieving the target characteristics at all temperatures are as follows:

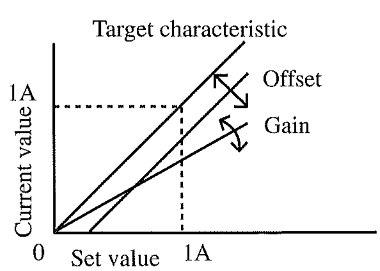

Figure 7 Offset and span of current sensing circuit

4.4.3 AMP1 and AMP2 offset adjustments

Since a leakage current at high temperature produces a current at AMP1 and AMP2 even when the set value is 0 mA, the output current at AMP1 and AMP2 is offset intentionally to be 0 (Figure 8). The overall offset and gain are adjusted as follows.

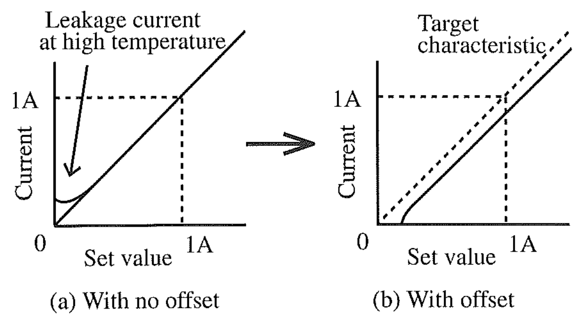

Figure 8 Offset adjustment of AMP1 and AMP2

4.4.4 Overall offset and gain

While measuring the sense register voltage at 1A where the output current specification is the strictest, we are making necessary adjustments for the optimum numbers of bits. As for the gain, the output resistances of AMP1 and AMP2 are adjusted for two bits. As for the offset, the constant current source of AMP3 is adjusted for three bits (Figure 9).

4.4.5 Zener diode zapping

Zener diode zapping is for the purpose of adjusting the resistance of the adjustment resistor by applying a high voltage to both ends of the diode to make a short circuit (Figure 10). This method was applied to all of the adjustment segments on the new driver IC.

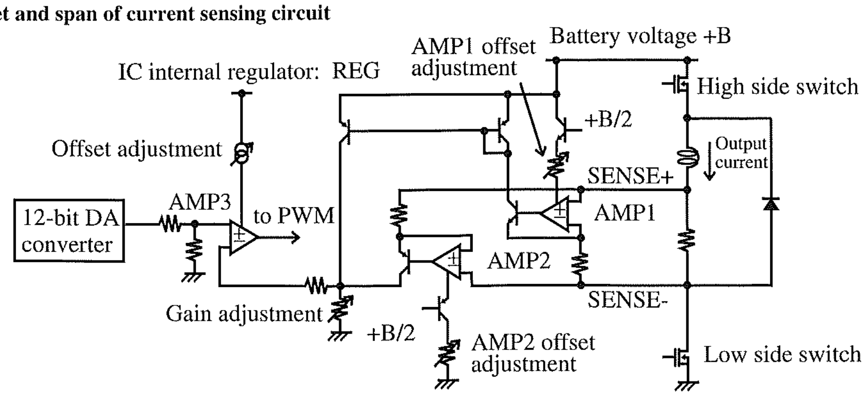

Figure 9 Total trimming

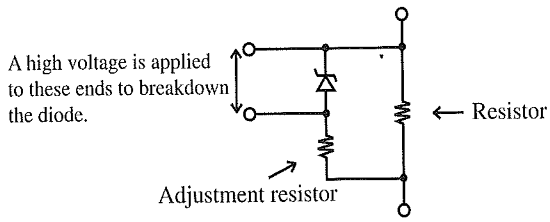

Figure 10 Zener diode zapping

4.5 High/Low Side Common Use

In linear solenoid drive control circuits using the current custom IC, the configuration of external parts used to be changed to select high or low side drive in accordance with the purpose of control. (Left in Figure 11)

A low side drive circuit is sometimes combined with a high side switch to improve the fail-safeness but is more costly with more output power devices and current detecting resistors. However, this combined circuit is used for transmission line hydraulic control and other controls requiring a high fail-safe function because it can cope with solenoid faults and short circuits caused by harness damage.

The new driver IC was developed to realize the low side drive function at a lower cost than the high side drive function based on the current custom IC and to succeed the conventional combination of control uses and drive systems. To achieve these purposes, two output power devices for the high and low sides were installed, the insertion position of the current detecting resistor was changed, and a high or low side drive switching function was incorporated. (Right in Figure 11)

Using common ICs for the high and low sides and sharing the external parts enabled the drive control circuit to be created with exactly the same configuration at low cost.

4.6 Multichannel Drive

In the future, it will be necessary to mount three or four linear solenoid control circuits per CPU. However, controlling several linear solenoids will lead to the problem of increasing microcomputer communications ports or duty output control channels.

To solve this problem, the new driver IC adopted master-slave serial communications.

4.6.1 ID terminal configuration of the new driver IC

The new driver IC has a 3-bit AD converter built in for high or low side drive selection and IC address assignment using external DC voltage. The 3-bit AD converter allows eight states to be selected and the microcomputer can control up to four ICs from a communications port of one channel. (Table 3, Figure 12)

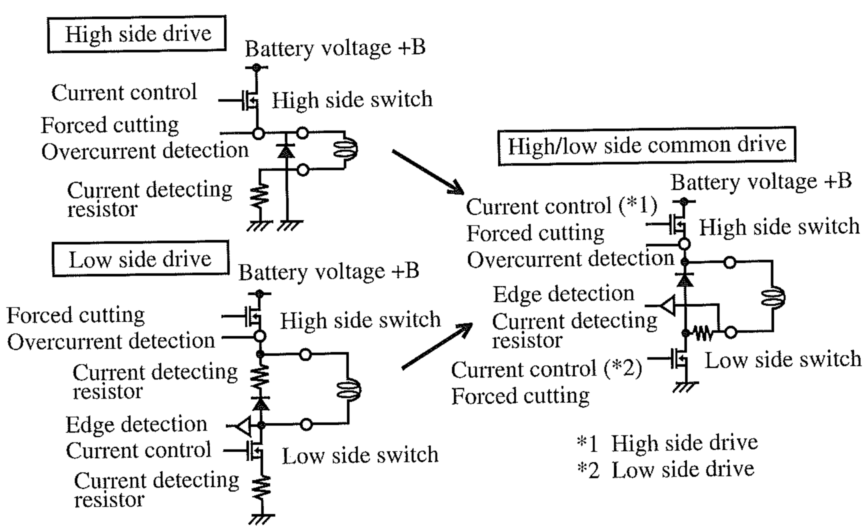

Figure 11 High and low side driver implementation

Table 3 ID terminal voltage, IC address, and drive

ID terminal voltage	Address	Drive
0 ~0.125Vcc	00	Low side
0.125Vcc~0.250Vcc	01	
0.250Vcc~0.375Vcc	10	
0.375Vcc~0.500Vcc	11	
0.500Vcc~0.625Vcc	00	High side
0.625Vcc~0.750Vcc	01	
0.750Vcc~0.875Vcc	10	
0.875Vcc~ Vcc	11	

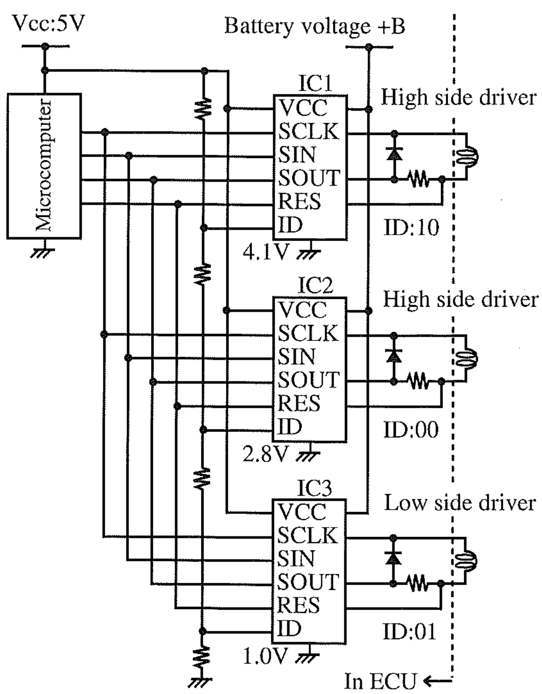

Figure 12 Multichannel drive application

4.6.2 Serial data configuration of the new driver IC

(1) Serial input

ID1	ID2	Parity	A	Current setting(12bits)

Parity: Odd

ID1, ID2: IC address

A: Forced cutting of current control (Cut: 1, Normal: 0)

(2) Serial output

Undefined (1)	ID1	ID2	e	d	c	b	a

		Abnormal	Normal
a:	Overheat diagnosis	1	0
b:	Previous communication error diagnosis	1	0
c:	Overcurrent diagnosis	1	0
d:	Control area monitor diagnosis	1	0
e:	Previous current setting	(Yes: 1)	(No: 0)

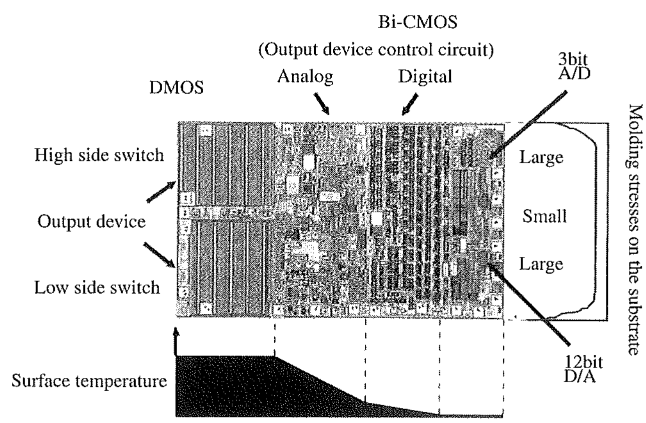

Figure 14 Chip layout pattern

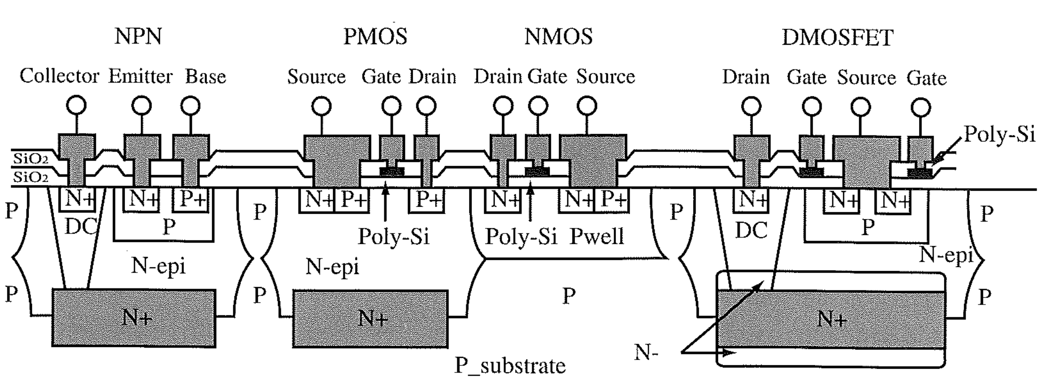

Figure 13 Device structure of BCD process

4.7 Semiconductor Process

4.7.1 Process

Figure 13 shows the cross-sectional structure of the devices used for the new driver IC. The output power devices are double diffused MOSFET (DMOSFET) of low ON resistance. The control circuit is a digital-analog mixed circuit based on Bi-CMOS technology. On-chip Zener diode zapping realized high-precision control with a single chip.

4.7.2 Chip layout

The surface temperature of the chip becomes highest at the output drivers because a current of up to 1 A or more flows. The 12-bit DA converter, 3-bit AD converter, and other circuits requiring high-precision control were arranged to avoid the thermal effects.

Since molding applies mechanical stress to the four corners of a chip, the 12-bit DA converter requiring especially high precision was positioned where the stress is minimal.

We determined the chip layout by considering the surface temperatures of the chip and the mechanical stresses on the substrate. (Figure 14)

5. Effects of Development

Compared with the current custom IC, the new driver IC realized output current precision was equal or higher, without the need of adjustments on the production line. Figure 15 shows the effects of development.

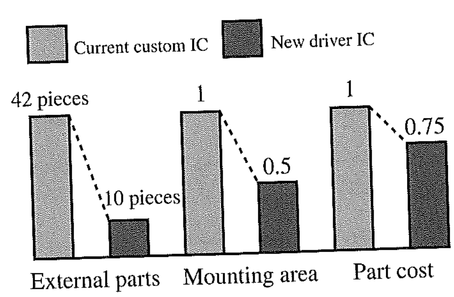

Figure 15 Effects of development

6. Future Development Efforts

The current ECU requires many manufacturing processes because surface-mount and other parts exist together. To enhance productivity, Fujitsu TEN is promoting surface mounting to cut down on the number of manufacturing processes and also to reduce the size and cost.

The new driver IC uses a ZIP package. For the next linear solenoid driver IC, we will adopt an SOP package of low thermal resistance to achieve the above objectives by reflow-only mounting. (Figure 16)

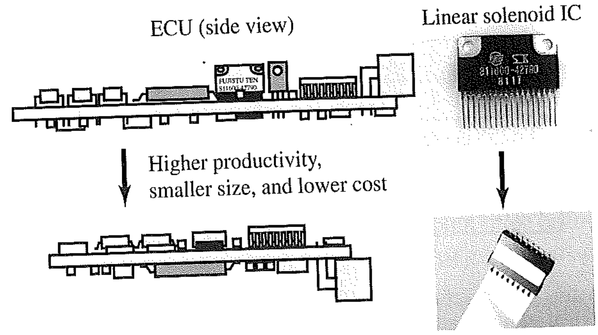

Figure 16 Side view of electronic control unit PCB

7. Conclusion

The new driver IC has the linear solenoid drive control circuit on a single chip. This not only reduced the number of external parts, mounting area, and system cost but also made adjustments unnecessary at the ECU manufacturing process, thereby significantly enhancing productivity.

Lastly, we'd like to express our gratitude to the related divisions for their cooperation.

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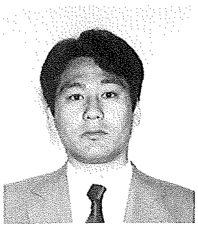

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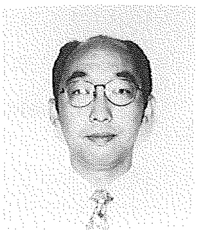

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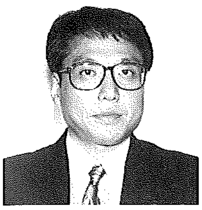

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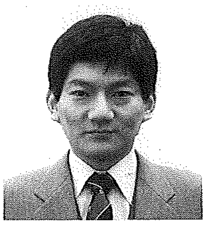

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