Abstract—In this paper, the synchronous AC/DC converter using super junction type power-MOSFET is proposed, and its electrical characteristics are discussed with experimental data. Related to further application of the advanced power-MOSFET for high current operation of large capacity synchronous AC/DC converter, the more reduction of on-state resistance is also studied with cooling down power-MOSFET device to the cryogenic temperature of liquid nitrogen and connecting power-MOSFET devices in parallel. As it is ordinary to have liquid nitrogen equipment for superconducting magnetic field coil, cooling down technology by liquid nitrogen is easy and useful to reduce on-state resistance of power-MOSFET. Parallel connection of many power-MOSFET devices is available to reduce total value of on-state resistance with increasing current rating and keeping current sharing among power-MOSFET devices equally.

Keywords-component: synchronous AC/DC converter; advanced unipolar power device; power-MOSFET; operational loss minimization

I. INTRODUCTION

To yield the magnetic field for plasma confinement, the power supply system should output its high DC current to the corresponding magnetic field coil. For that purpose, many large capacity AC/DC converters are required to be installed as the main part of power supply system. For designing the large capacity AC/DC converter, it is important issue that the operational loss of AC/DC converter should be minimized to get high efficiency and good economical solution in operation. To reach operational loss minimization, the on-state resistance in power electronics device as switching unit of AC/DC converter is the key parameter. The unipolar power electronics device, the typical one being power-MOSFET, has many advantages for application to large capacity AC/DC converter. And, power-MOSFET device is well known one to be used in various AC/DC converter circuits including synchronous one. Recently, an advanced unipolar power electronics device has been developed, namely trench gate type or super junction type power-MOSFET, and has some excellent characteristics of lower on-state resistance, which promises to reduce its conductive loss, than that of conventional power-MOSFET.

The synchronous rectifier means an AC/DC converter to turn on the switching element in every half cycle with synchronizing AC voltage polarity. Fig. 1 shows briefly the basic circuit of single phase synchronous rectifier with one power-MOSFET device. The secondary winding of transformer has one main winding to be connected with load through power-MOSFET, and the other winding, which is connected with gate terminal (G) of power-MOSFET, is for supplying the gate signal voltage to turn on or turn off power-MOSFET.

The main current path is from source terminal (S) to drain terminal (D) when the voltage polarity is positive on source side. Power-MOSFET has parasitic body diode in itself, which can flow current also from source to drain. So, source side voltage being positive, the main current flows through body diode part without any gate signal. It is undesirable that body diode carries high current, because the operational loss in power-MOSFET comes larger by high resistance of body diode part. So, the gate signal must be given to power-MOSFET in current conduction period to avoid current flowing through body diode.

When the primary AC voltage is supplied and the half cycle of positive polarity continues, the secondary voltage is positive on source and gate terminals, which means turning on power-MOSFET, and the secondary current flows to load through source and drain terminals. On the other hand, when the primary AC voltage is in negative half cycle, the secondary voltage is negative on source and gate terminals, which means turning off power-MOSFET, and the secondary current does not flow. As the result, the secondary current can flow only in the positive half cycle, and becomes DC current equivalently.

II. ADVANCED UNIPOLAR POWER ELECTRONICS DEVICE

In this study, the super junction type power-MOSFET is investigated, which is one of unipolar power electronics devices and an advanced device based on crystallized Si material. Power-MOSFET is well known device to be applied to high efficient power supply, not so large capacity one. To use power-MOSFET for large capacity power supply, it is required that its on-state resistance is lowered with high withstand voltage specification.
The super junction type power-MOSFET is one of advanced power electronics devices to achieve lower on-state resistance value in higher voltage region, which has excellent electrical characteristics to be applied to high current AC/DC converter. A super junction type power-MOSFET is investigated on its static voltage-current characteristics and the on-resistance value. The super junction type power-MOSFET SPA20N60C3 has the voltage and current ratings of 650V and 20.7A respectively. And also, the temperature dependence of the voltage-current characteristics is clarified. Considering to cool down the power electronics device for high current operation, the static voltage-current characteristics are measured in room and liquid nitrogen temperature. [1]

As shown in Fig. 2, the static voltage-current characteristics of SPA20N60C3 are measured in both of positive and negative directions in room temperature. The voltage-current characteristics show the linear one as same as that of resistance, whereas the voltage-current characteristics of body diode of power-MOSFET is dominant in the negative direction. The on-state resistance value in room temperature is estimated as about 0.16 ohm. The static voltage-current characteristics of SPA20N60C3 are also measured in liquid nitrogen temperature, which are shown in Fig. 3 in both of positive and negative directions. The voltage-current characteristics show the linear one as same as those in room temperature, whereas the voltage value is lower than that in room temperature. The characteristics of body diode of power-MOSFET is not included in the negative direction because it remains in the similar region of the voltage-current characteristics in room temperature. The on-state resistance value in liquid nitrogen temperature is estimated as about 0.035 ohm, which is 20 % of that in room temperature approximately. The built-in voltage of body diode of power-MOSFET is about 0.7 V in room temperature and about 1.0 V in liquid nitrogen temperature respectively.

As the measured results of voltage-current characteristics of super junction type power-MOSFET are mentioned above, the reduced on-state resistance in liquid nitrogen temperature can promise to conduct high current without increasing the operational loss of AC/DC converter. Furthermore, Si-based super junction type power-MOSFET would be expected to contribute to high efficiency operation of large capacity power supply.

III. SINGLE PHASE FULL-BRIDGE SYNCHRONOUS RECTIFIER WITH POWER-MOSFET

To output the continuous DC current, the single phase circuit in Fig. 1 should be modified to three phase type one. As the first step to develop three phase type one, the single phase full-bridge synchronous rectifier, which is the unit of three phase type synchronous rectifier, is constructed and tested. Fig. 4 shows the schematic diagram of single phase full-bridge synchronous rectifier for testing operation with small voltage and current. The symbol of power-MOSFET means one super

![Figure 1. Conceptual diagram of synchronous rectifier](image1)

![Figure 2. The static voltage-current characteristics of super junction type power-MOSFET(SPA20N60C3) in room temperature](image2)

![Figure 3. The static voltage-current characteristics of super junction type power-MOSFET(SPA20N60C3) in liquid nitrogen temperature](image3)
junction type power-MOSFET SPA20N60C3 investigated in the previous section. Two switching units of super junction type power-MOSFET devices are used for converting AC to DC in full cycle period. According to the AC voltage polarity, each device is supplied with synchronized gate signal voltage to flow the current through main part of power-MOSFET element, not through the body diode. [2]-[3]

Each power-MOSFET device is triggered in every half cycle synchronizing to the AC voltage. In the positive half cycle, the upper side power-MOSFET (FET1) turns on to flow the current as mentioned in the previous section. To output the current in the negative half cycle period, the inverse side power-MOSFET (FET2) is to flow the current as same process as in the positive half cycle. Fig. 5 shows the AC voltage waveform ($V_v$) and the gate signal voltage waveforms for each power-MOSFET device, which are square voltage signals ($V_{GS1}$ and $V_{GS2}$ for FET1 and FET2 respectively). The return path of the current is connected to the middle point of secondary winding to close the circuit for keeping current in each half cycle.

In Fig. 6, The AC voltage ($V_v$) is the voltage appearing in secondary side of transformer and the drain-source voltage ($V_{DS1}$) is the voltage appearing in the upper side power-MOSFET (FET1). It is observed that the power-MOSFET (FET1) is turning on and turning off in every 180 electrical degrees with synchronizing to the applied AC voltage ($V_v$). The final waveform of output voltage ($V_o$) is similar to that of a normal single phase full-bridge circuit with diode rectifier, and it is also shown that the inverse side power-MOSFET (FET2) is switched on/off according to the corresponding gate signal voltage.

IV. PARALLEL OPERATION OF SUPER JUNCTION TYPE POWER-MOSFET DEVICES

As the results of the measured voltage-current characteristics of super junction type power-MOSFET SPA20N60C3, it is expected that the total on-state resistance of parallel connected power-MOSFET devices is to be lowered by the number of parallel connection. In the current and temperature range of measurement, the voltage-current characteristics are almost linear in positive and negative directions, as same as that of resistor, which means that the parallel connected devices operate simultaneously well like one large size or high rating power-MOSFET device.

As parallel connection of power-MOSFET devices is important technique for high current operation, two super junction type power-MOSFET devices are connected in parallel as the upper side power-MOSFET branch shown in Fig. 7. To test current sharing in parallel connected devices, those are arranged to keep the circuit configuration equally in each other. For the fundamental research on reduction of on-state resistance of parallel connected power-MOSFET devices, it is
expected that the parallel connected power-MOSFET devices show the total on-state resistance value of two parallel devices. As shown in Fig. 8, the upper side power-MOSFET devices (FET1 and FET2) flow their current equally, and the current sharing in the parallel devices is well in every half cycle. The inverse side power-MOSFET (FET3) is to flow the current in other half cycle, and the current $I_3$ of FET3 is just twice of the current $I_1$ or $I_2$ shown in Fig. 8. In the case of more power-MOSFET devices being connected in parallel for application to large capacity AC/DC converter, the same trend to keep current sharing equally is the important issue. For future development, the current and capacity ratings of super junction type power-MOSFET should be grown to decrease the parallel number of devices.

V. CONCLUSION

Super junction type Power-MOSFET has the linear voltage-current characteristics and the low on-state resistance in bi-directional positive and negative polarities. The on-state resistance of power-MOSFET has the same resistive trend as normal resistor, which shows much lower resistance value in low temperature and/or in parallel connection. Such advantages will promise that the operational loss of high current AC/DC converter using parallel connected super junction type power-MOSFET devices is reduced in low temperature condition. The converter system including power-MOSFET devices will be cooled down in liquid nitrogen to make its operational loss extremely low. And, as another type advanced unipolar power device, SiC-based power-MOSFET will be developed for lower on-state resistance and higher operational temperature than that of conventional Si-based power-MOSFET. The large capacity AC/DC converter is required to be low operational loss system for high efficiency. To reduce the operational loss, parallel connected power-MOSFET devices should lower the total on-state resistance in low temperature like that of liquid nitrogen. As the high DC current and low operational loss converter system, the synchronous rectifier with power-MOSFET is proposed. The advantage of synchronous rectifier using power-MOSFET is to minimize total on-state resistance of parallel connected devices. The principle of basic operation of synchronous rectifier is described, and is tested experimentally with single phase full-bridge circuit. The operational results of single phase synchronous rectifier are successful, and super junction type power-MOSFET device, which is an advanced unipolar power electronics device, is demonstrated to be applied to synchronous rectifier.

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REFERENCES

